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CONTINUOUS CURRENT ARMATURES

CONTINUOUS CURRENT ARMATURES

THEIR WINDING AND CONSTRUCTION

A HANDBOOK FOR STUDENTS, DESIGNERS
AND PRACTICAL MEN

BY

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"Die Ankerwicklungen und Ankerkonstruktionen," by Professor Arnold.

"Armature Windings," by Parshall and Hobart.

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"Dynamo-Electric Machinery," by S. P. Thompson.

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PREFACE

THIS little volume was originally intended as a translation of Professor Arnold's book on the same subject. It was, however, thought that this subject could be made clearer by omitting a discussion of all those windings which, though possible, are but seldom employed for standard machines of medium size. Thus, while following Professor Arnold's splendid method of discussing the windings, the discussions have been restricted to the commonly employed drum windings only.

By means of the rules given in this volume, the reader will, if necessary, always be able to design any other winding, not actually discussed here. The explanations are given in a very popular manner, so that anybody, possessing an elementary knowledge of the principles of continuous current machines should be able to understand them fully.

Though the work is mainly intended for students and designers, the author feels sure that also the intelligent workman (such as the armature winder, etc.) will be able to understand it, and thus gain a good knowledge of the work in which he is employed.

The author's thanks are due to Mr. Raymond Wood, of Halifax, for his kind assistance in reading the proofs.

C. KINZBRUNNER.

November, 1905.

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CONTINUOUS CURRENT ARMATURES

THEIR WINDING & CONSTRUCTION

CHAPTER I

THEORY OF WINDINGS

1. Introduction

According to the law of induction, an E.M.F. is induced in a conductor which is moving in a magnetic field. The simplest case of induction is shown in Fig. 1, where a wire AB, having a length of l cm.,

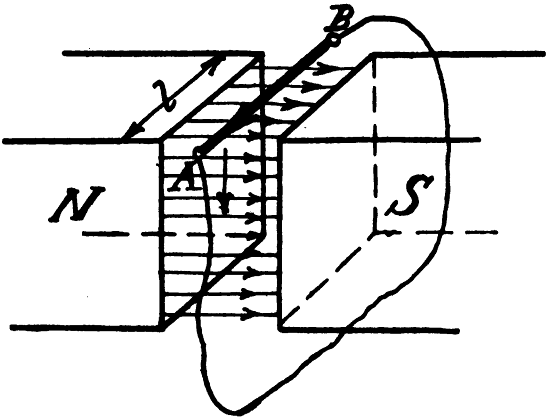

Fig. 1.

is moved with a uniform speed v cm. per second in a uniform magnetic field, the induction of which is B lines of force per square centimetre.

Then, according to a fundamental law, the E.M.F. induced in the wire AB—

$$E = Blv \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (1)$$

in absolute units, or—

$$E = Blv10^{-8} \quad . \quad . \quad . \quad . \quad (2)$$

in volts.

It must be understood that for (l) not the total length of wire must be inserted, but only that length which is being transversed by the lines of force.

With regard to the direction of the E.M.F. induced, the following rule may be applied :—

Hold the palm of the right hand against the lines of force, the thumb in the direction of motion, then the fingers point out the direction of the induced E.M.F. (see Fig. 2).

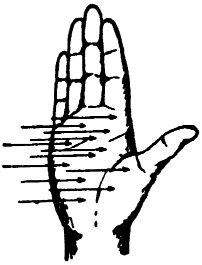

Fig. 2.—The Hand Rule.

Supposing, now, that we connect the ends A, B of the conductor by means of a metal wire, then a current will obviously flow through the now closed circuit. The direction of this current will be the same as that of the E.M.F. induced, and the current can naturally flow only as long as an E.M.F. is induced in the wire.

To produce, therefore, a constantly flowing current, we must either move a wire constantly in the same direction and in a field of uniform strength, so producing a continuous current, or, we could move the wire in a field as shown in Fig. 1, and after having arrived at the end of the field, could reverse the direction of motion of the wire; this would obviously give an alternating current.

The first of the above alternatives leads to the homopolar machine, the principle of which is shown in

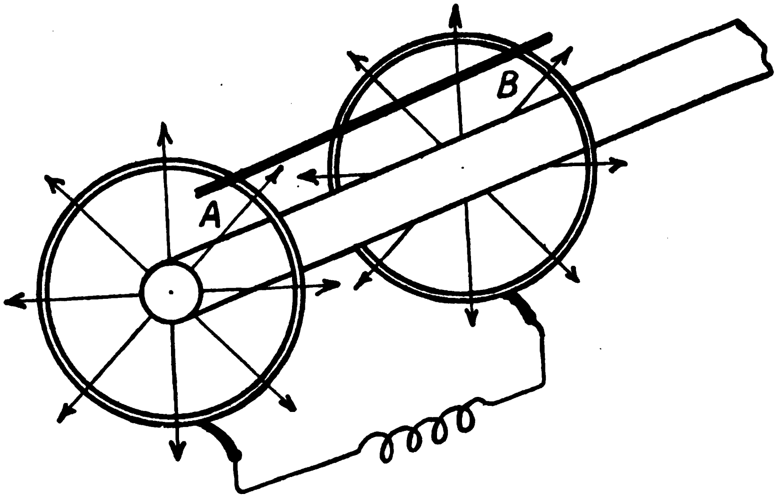

FIG. 3.—Principle of a Homopolar Dynamo.

Fig. 3. The conductor AB turns round the axis of one pole of a magnet. The circuit is closed by two slip-rings with a connecting wire between them. It will be seen that, while rotating, the conductor AB is cutting a field of uniform strength. Since the direction of motion is always the same, the direction of the E.M.F. and the current induced are constant.

Machines on this principle have actually been built in many different forms. Their chief disadvantage is, that the E.M.F. is induced in one conductor only, and consequently very high inductions and very high peripheral speeds are necessary for comparatively low voltages. A simple calculation will illustrate this. Supposing we make the length of the conductor equal to 1 metre, the induction of the field B = 15,000, and assume the comparatively high peripheral speed of 30 metres per second, then

$$E = 15{,}000 \times 100 \times 3000 \times 10^{-8} = 45 \text{ volts}$$

Thus, notwithstanding the high induction and peripheral speed, the voltage is far too small for most purposes.

To obtain higher voltages with homopolar machines, we must use several conductors, take the current off each of these by means of separate slip-rings, and connect them in series outside the machine. The objection to such an arrangement is the large number of slip-rings necessary, and the large voltage-drop and ohmic losses in connection with the collection of the current. Of course all these troubles can be overcome by means of a suitable design; homopolar machines have certainly a great future in connection with steam-turbines, as has been shown lately by the successful working of such machines for relatively high outputs.*

The most usual method for adding the E.M.F.'s induced in several conductors is shown in Fig. 4. N and S are the poles of an ordinary four-polar field-magnet developed into a straight line. By connecting together the conductors which are simultaneously under the influence of poles of different polarity, the E.M.F.'s induced in the single conductors are added to each other. Instead of having only one wire under each pole, we may arrange for any number of wires being connected in this manner, and can thus produce any voltage required.

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* See Noeggerath, "Homopolar Dynamos." Lecture read before the A.I.E.E., January 27, 1905.

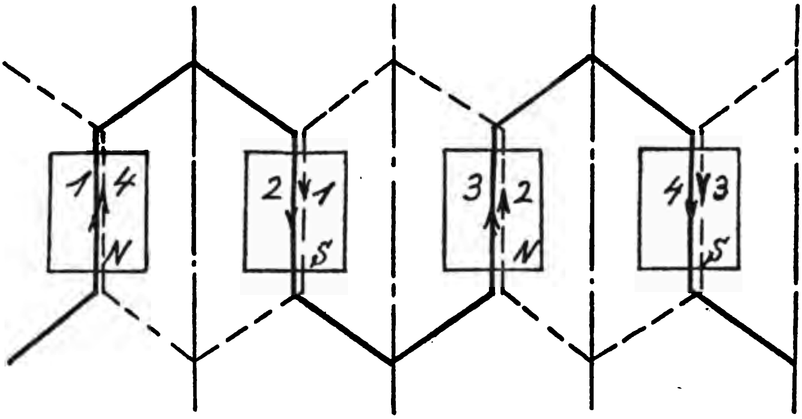


Fig. 4.—Series Connection of Conductors.

2. The Commutator

A glance at Fig. 4 will show that the current produced in this way cannot be a direct current, *i.e.* a current of constant strength and direction. For, in the position of the wires shown in full lines, the current is flowing upwards in the wires 1 and 3, and downwards in 2 and 4. When the wires are in the position shown by dotted lines, the current is flowing downwards in

1 and 3, and upwards in 2 and 4, *i.e.* it has been reversed. The current thus produced is an alternating current. To rectify this alternating current into a direct one, a special commutating device, the commutator, must be used.

The principle of commutation is shown in Fig. 5. It will be seen that the ends of the armature-winding are connected to two half-rings, which are insulated from each other. Two brushes B_1 and B_2 are sliding on the rings at two diametrically opposite points. It is obvious that the brush B_1 is always in contact with the wire which is under the influence of the north pole, and brush B_2 with that which is under the influence of the south pole. The polarity of each of these brushes will, therefore, always be the same, and the current taken off these brushes will be a continuous or direct current.

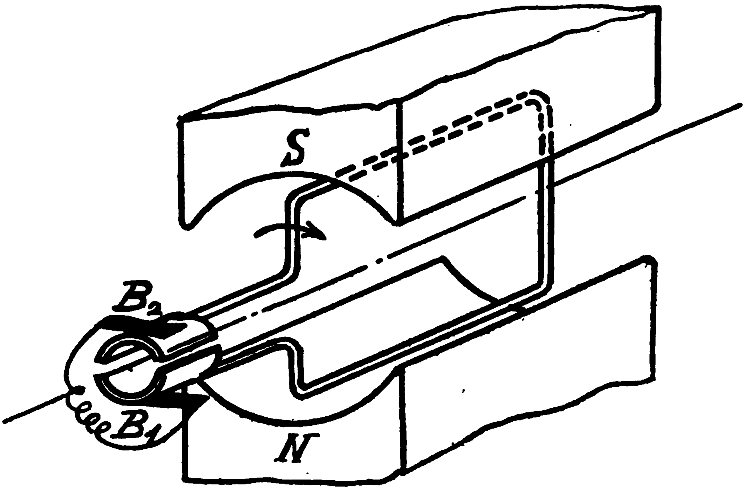


Fig. 5.—Principle of Commutation.

The arrangement as shown in Fig. 5 is not suitable for large machines, on account of the considerable variations of the E.M.F. (and hence the strength of the current) during each revolution. When passing through the neutral zone (*i.e.* the zone between the pole-tips) the E.M.F. induced in the wires will be zero, while it will be a maximum in the position of the wires as indicated in Fig. 5. The instantaneous values of the E.M.F. (and the current) induced are shown in Fig. 6 as function of the position of the wires. To reduce these variations of the current, we have to increase the number of coils and commutator segments. Fig. 7 shows the arrangement of four coils

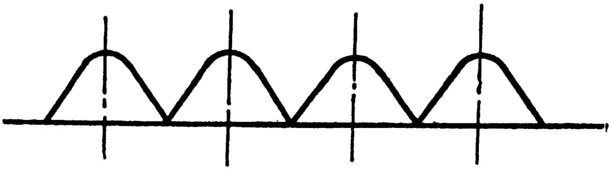


Fig. 6.—Wave form of E.M.F. as produced by an Armature with Two Commutator Segments.

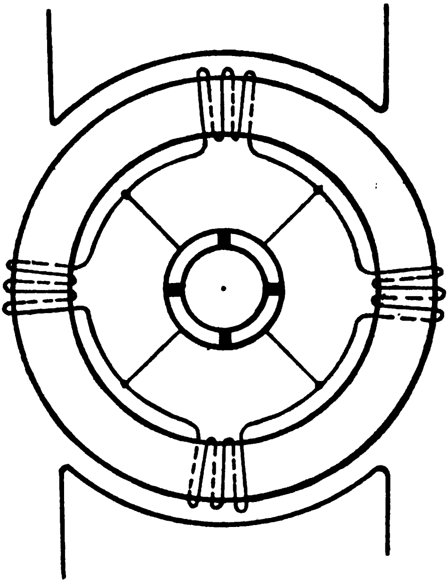


Fig. 7.—Armature with Four Coils and Four-part Commutator.

and a four-part commutator. The maxima and minima of the currents in the two coils are now obviously displaced by 90°, and we obtain the total current by adding the abscissæ of the two curves I and II (Fig. 8). From the resulting curve, III, we see that both the absolute and the relative variation of the current (referred to the maximum) have become smaller. By further increasing the number of coils and commutator sections, we are able to reduce the variations of the current to any minimum required.

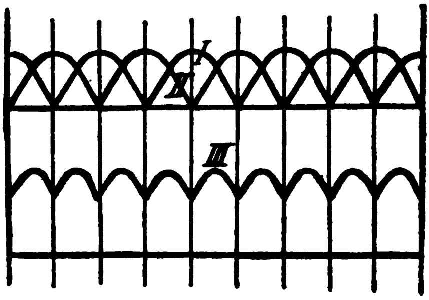


Fig. 8.—Resultant Wave Form of E.M.F. produced by an Armature with Four Coils and Four Commutator Segments.

The following table shows the variation of the current in per cent. as a function of the number of commutator sections per pole :—

Number of commutator sections per pole ...	1	2	10	15	30	45
Variation of current in per cent.	50	14	0·61	0·28	0·07	0·03

Thus a winding for a continuous-current armature should have several coils and commutator sections per pole.

3. Types of Windings

The two main types of continuous-current windings are—

1. Ring Winding.
2. Drum Winding.

The diagram of a ring winding is shown in Fig 9. The characteristic feature of this winding is that the connecting conductors are carried through the interior of the ring core, and the winding thus forms one continuous spiral, from which, at equal intervals, branch connections are led to the commutator.

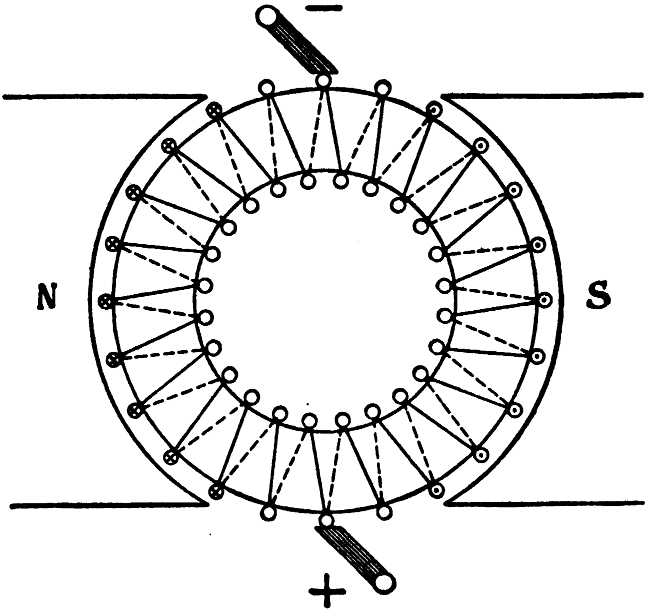


Fig. 9.—Ring Armature.

The diagram of a simple drum winding is shown in Fig. 10. The characteristic feature of this winding is, that the conductors are arranged only on the circumference and on the sides of the armature, and that each conductor is connected to one which is under the influence of an opposite pole.

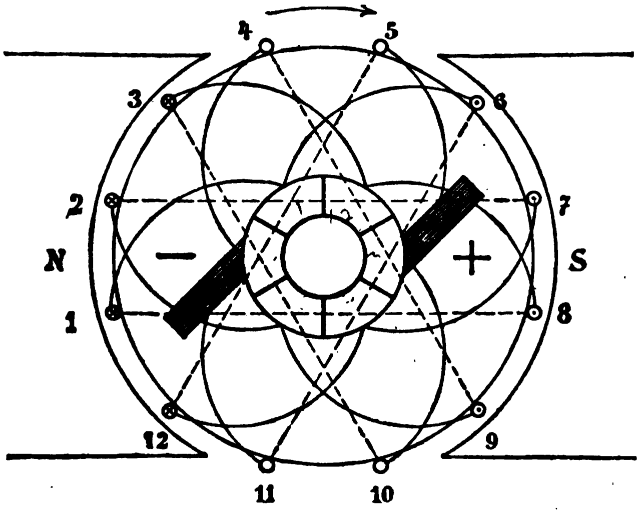


Fig. 10.—Drum Armature Connections.

Notwithstanding its great advantages, the ring winding is used in special cases only. Modern machines of average voltages are almost exclusively provided with drum-wound armatures, and these only will be considered here.

4. Explanation of Terms

As mentioned above, the characteristic feature of a drum winding is the connection of one wire with another which is under the influence of a pole of opposite polarity. These connections can, however, be made in different ways, and accordingly we have to distinguish between Lap Windings (sometimes called Loop Windings) and Wave Windings.

Lap Windings.—If the conductors are connected with each other in such a manner as to form loops, so that, starting from one commutator section and passing through a part of the winding, we arrive at a commutator section next to the one we started from, the winding is called a lap or loop winding.

Fig. 11 represents such a winding for a four-pole

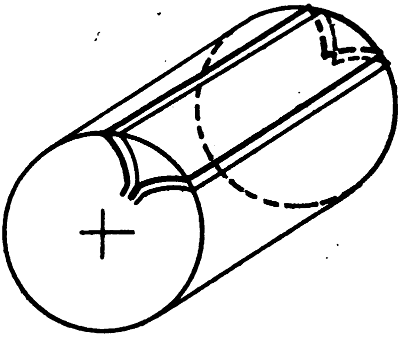
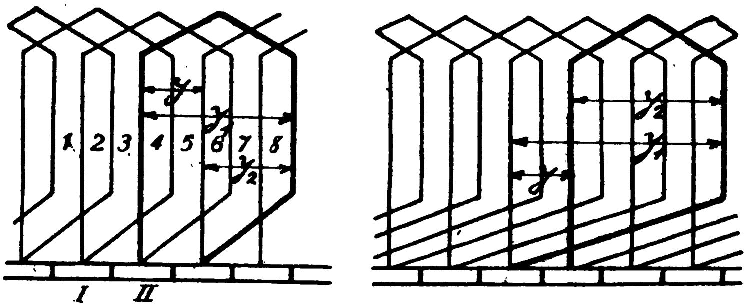


Fig. 11.—Lap Winding.

drum armature, the development of which into a straight line (Fig. 12) shows more clearly the forming of the loops and the manner of their overlapping.

A glance at Figs. 12 and 13 will show that there are two ways of obtaining a lap winding. The loop may either be open, as in Fig. 12, or closed, as in Fig. 13. The only difference between these two windings lies, as we shall see later on, in the winding pitch, but there is no difference between them from the electrical point of view.

Wave Windings.—If the connections between the single conductors (or coils) advance continually in one direction, so that, beginning from one bar and passing through a part of the winding (one coil), we do not arrive at a commutator section next to the one we started from, but at one being at a considerable distance from it, the winding is called a wave winding. It represents itself in a zigzag or wave shape. Fig. 15 shows a wave winding for a four-pole machine. The development of this winding into a straight line is shown in Fig. 16, and shows more distinctly the wave form.



FIGS. 12, 13.—Lap Windings.

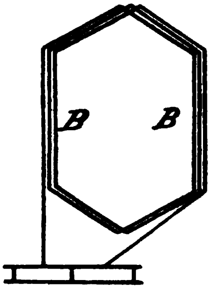


FIG. 14.—Lap Winding.

Winding Element or Element.—That part of a winding which lies between two commutator sections is called a winding element. With a drum winding an element consists of at least two conductors, but may consist of any larger, even number. In Figs. 12, 13, and 16 each element consists of one turn or two conductors, while in Figs. 14 and 17 the same elements consist of three turns or six conductors.

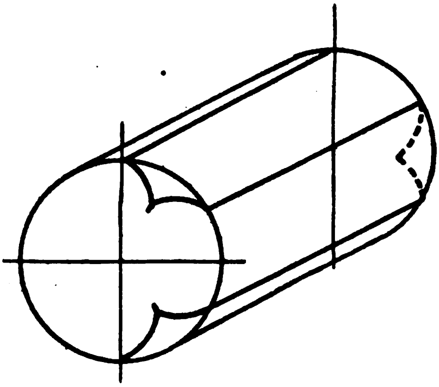
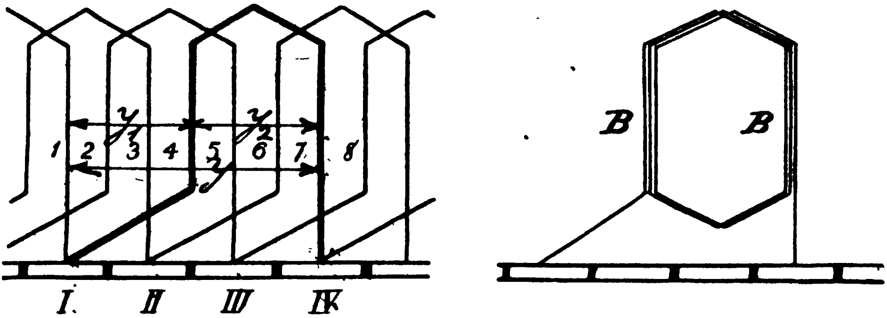


FIG. 15.—Wave Winding.

The simplest winding element is the coil, which again may consist of either one or several turns. The



FIGS. 16, 17.—Diagrams of Wave Winding.

term "coil" is commonly used in a mechanical sense, indicating that a number of turns are wound together, as, for instance, in the case of a former-coil.

If we call G the number of winding elements on one armature, and K the number of commutator sections, then it follows from the above definition of the term "winding element" that

$$G = K$$

Let us further call g the number of conductors per element, and Z the total number of conductors on the armature; then

$$Z = gK = gG$$

As explained above, each element consists of at least two conductors. Where an element consists of more than one turn, thus of more than two conductors, we shall, for the sake of simplicity, in our future considerations combine all the conductors on each side of the winding element, and call this combination of conductors a "winding bar," or, shortly, "bar." Thus each element consists of two bars, and each bar may consist of any number of wires. In Figs. 14 and 17 each bar consists of three wires, and is marked "B."

Pitch.—The distance between the beginning of one winding element and the beginning of the next element connected to the first one is called "pitch." This pitch may be measured either by the number of bars passed, or by the number of commutator sections passed. In the former case it is called winding pitch, for which the symbol y is generally used; in the latter case it is called commutator pitch (y_k).

An example will make this clear. In Fig. 12 is shown the diagram of a lap winding. Bars 1 and 6 form one, bars 3 and 8 another winding element. The distance between the beginning of the first element (bar 1) and the beginning of the next element (bar 3) is obviously $3 - 1 = 2$. Thus the winding pitch is in this case 2. With regard to the commutator pitch, it will be seen that bar 1 is connected with commutator section I, while the beginning of the next element, viz. bar 3, is connected with commutator section II. Thus

$$y_k = \mathrm{II} - \mathrm{I} = 1$$

Fig. 16 shows the diagram of a wave winding. The winding pitch is here again equal to the distance between the beginning of the element (*i.e.* bar 1) and the beginning of the next element connected to the first one (*i.e.* bar 7). Thus

$$y = 7 - 1 = 6$$

From Fig. 16 it also follows directly that $y_k = 3$.

In both the lap and the wave winding the pitch y is combined of the front and back pitch y_1 and y_2 respectively. y_1 and y_2 represent in all cases the distances between the bars connected with each other; the total pitch, y, is equal to the algebraic sum of y_1 and y_2. Thus, in Fig. 12, $y_1 = +5$, and $y_2 = -3$; hence

$$y = +5 - 3 = +2$$

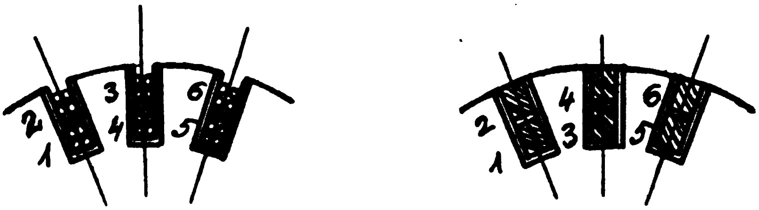
In Fig. 16, $y_1 = +3$, $y_2 = +3$; hence

$$y = +3 + 3 = +6$$

The following table contains the usual terms and the corresponding symbols:—

Total number of conductors	Z
Number of winding elements	G
Number of winding bars	N
Number of conductors per winding element	g
Number of commutator sections	K
Total winding pitch	y
Part pitches	y_1, y_2
Commutator pitch	y_k
Number of poles	$2p$
Number of armature sections in parallel	$2a$

For drawing a winding diagram it is convenient to number the winding bars. This should be done as indicated in Figs. 18 and 19. Fig. 18 shows the numbering for hand-wound, Fig. 19 that for former- or bar-wound, armatures.



Figs. 18, 19.—Methods of Numbering Conductors on Armature.

5. Drum Windings

(a) PARALLEL WINDINGS

The winding of every drum armature consists of as many armature sections as there are poles. Thus a bipolar armature consists of two, a ten-pole armature of ten sections, etc.

The characteristic feature of a parallel winding is, that all the armature sections are connected in parallel; thus

$$a = p \text{ (see Figs. 20 and 21)}$$

With regard to the pitch, the following conditions must be fulfilled:—

$$y_1 = \frac{N \pm b}{2p} \pm 2 \quad . \quad . \quad . \quad . \qquad (3)$$

$$y_2 = \frac{N \pm b}{2p} \quad . \quad . \quad . \quad . \quad . \quad . \qquad (4)$$

$$y_k = \pm 1 \quad . \quad . \quad . \quad . \quad . \quad . \quad . \qquad (5)$$

For b any *even* number may be taken; it must not, however, be too large, as otherwise there would be a possibility of two wires connected with each other coming under the influence of poles of the same polarity, so that the E.M.F.'s induced in these wires would oppose each other. This is shown in Fig. 22. We may connect wire 1 with either 2 or 3, but we must not connect it with 4, as in this case the E.M.F. induced in 1 would be equal and opposite in direction to that induced in 4; the resultant voltage would be zero.

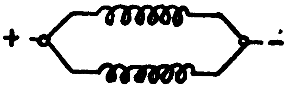


Fig. 20.—Diagram for a Two-pole Parallel Winding.

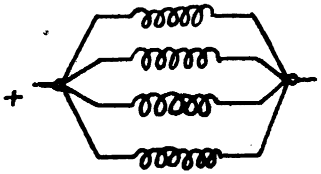


Fig. 21.—Diagram for a Four-pole Parallel Winding.

It follows, therefore, that b must be selected so as to make y_1 and y_2 about equal to the pole pitch (*i.e.* the distance from centre to centre of two consecutive poles).

Both y_1 and y_2 must be odd numbers. This rule applies to all ordinary drum windings.

y_1 and y_2 must have opposite signs; if the one is positive, the other must be negative, and *vice versâ.*

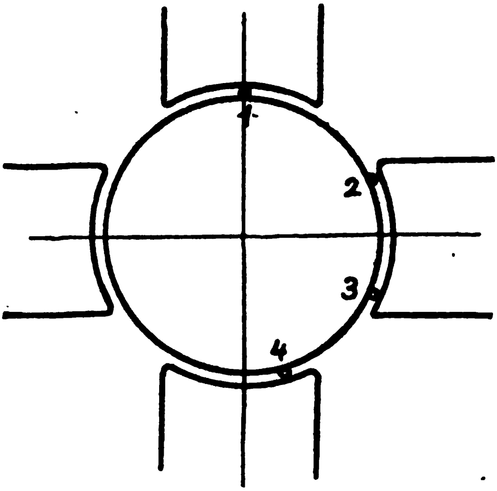


FIG. 22.—Winding Pitches.

Their algebraical sum, *i.e.* the total pitch y, is thus always equal to ±2.

The drum parallel winding is *always* a loop winding, and the number of collecting points on the commutator must always be equal to the number of poles.

The current flowing through each conductor

$$c_1 = \frac{C}{2p} \quad . \quad . \quad . \quad . \quad . \quad . \qquad (6)$$

where C stands for the total armature current. The cross-section of the conductors should be selected according to this current (c_1).

The greatest possible potential difference between two consecutive bars is equal to, or slightly smaller than the terminal voltage.

EXAMPLE I

Bipolar armature. N = 26, $2p = 2$, K = 13. According to formulæ (3) and (4)—

$$y_1 = \frac{26 \pm b}{2} \pm 2, \qquad y_2 = \frac{26 \pm b}{2}$$

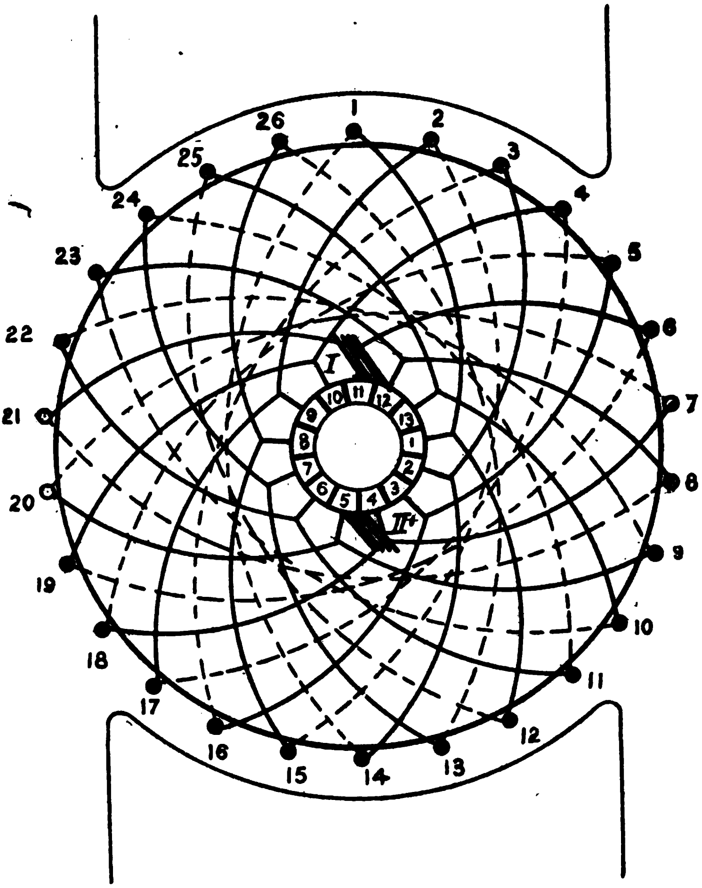


FIG. 23.—Diagram of Parallel Winding, with N = 26, $y_1 = +11$, $y_2 = -13$.

For b we may, as mentioned above, insert either 0 or any even number. In this particular case we make $b = 0$, and get thus—

$$y_1 = 15 \text{ or } 11, \quad y_2 = 13$$

In Fig. 23 the winding diagram is shown for $y_1 = 11$ and $y_2 = -13$.

For the brush position, as shown in the diagram, the path of the current in the armature is as follows:—

$$\text{Brush I}\begin{matrix}\diagup 6-19-4-17-2-15-26-13-24-11-22-9 \diagdown\\ \diagdown 23-10-25-12-1-14-3-16-5-18 \diagup\end{matrix}\text{Brush II}$$

It will be seen from this table that the current branches at brush I flows through the two parallel connected branches, both branch-currents combining again under the second brush, II.

Supposing we make for the above armature $b = +2$, then

$$y_1 = 14 \pm 2, \ y_2 = 14$$

This is an impossible winding, as both y_1 and y_2 are even numbers. To show the impossibility of this winding, Fig. 24 has been drawn, where $y_1 = 16$, $y_2 = -14$. It will be noticed that this gives an incomplete winding, since it is closed before all the conductors are connected up.

With $b = -2$ the winding is also impossible, but becomes possible for $b = \pm 4$, for in this case

$$y_1 = 17 \text{ or } 13, \ y_2 = 15$$

or—

$$y_1 = 13 \text{ or } 9, \ y_2 = 11.$$

All these values give possible windings, but only those should be taken which are approximately equal to the pole pitch (which in this armature is $\frac{26}{2} = 13$).

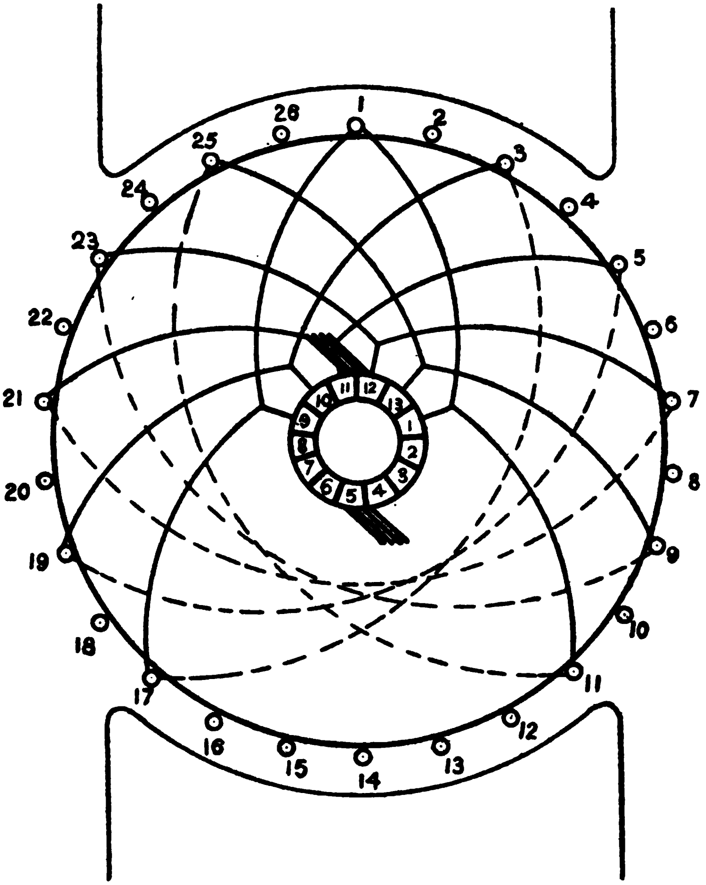


FIG. 24.—Diagram of Parallel Winding, with $N = 26, y_1 = 16, y_2 = -14$.

With $b > 0$ the winding is said to have a shortened pitch. The following is an example of such a winding :—

EXAMPLE II

Bipolar armature with shortened pitch. $N = 24$, $2p = 2$, $K = 12$, $b = -6$; hence

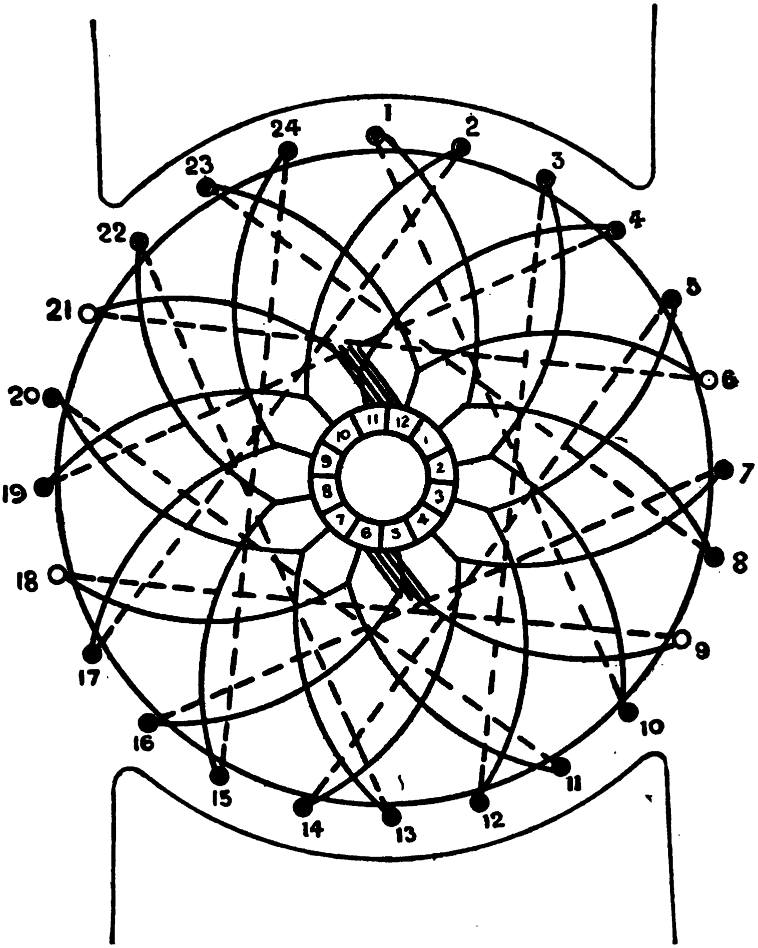


FIG. 25.—Diagram of Parallel Winding, with Shortened Pitch, where $N = 24$, $y_1 = +7$, $y_2 = -9$.

$$y_1 = \frac{24-6}{2} - 2 = 7, \qquad y_2 = \frac{24-6}{2} = 9$$

It will be seen from the diagram for this winding (Fig. 25) that the currents flowing in the armature conductors between the short-circuited bars are of opposite direction, so that their resultant magnetic action is zero. It follows, that a shortening of the pitch, or, what is the same, an increase of *b*, tends to reduce the armature reaction.

Commonly *b* is made as big as allowable, having regard to the conditions mentioned above.

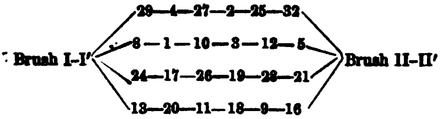
EXAMPLE III

Slotted armature, hand-wound. $N = 32$, $2p = 4$, $b = -4$.

$$y_1 = 9, \ y_2 = -7$$

The diagram for this four-polar armature is shown in Fig. 26. The numbering of the wires should, as explained before, be such that the bars on the top of alternate slots should bear even and odd numbers alternately (see also Fig. 18).

For the brush position, as indicated in the diagram, the path of the current in the armature is as follows :—



Hand-wound armatures are but seldom made nowadays, except in the case of bipolar armatures. By far the majority of multipolar armatures are provided with former windings or bar windings.

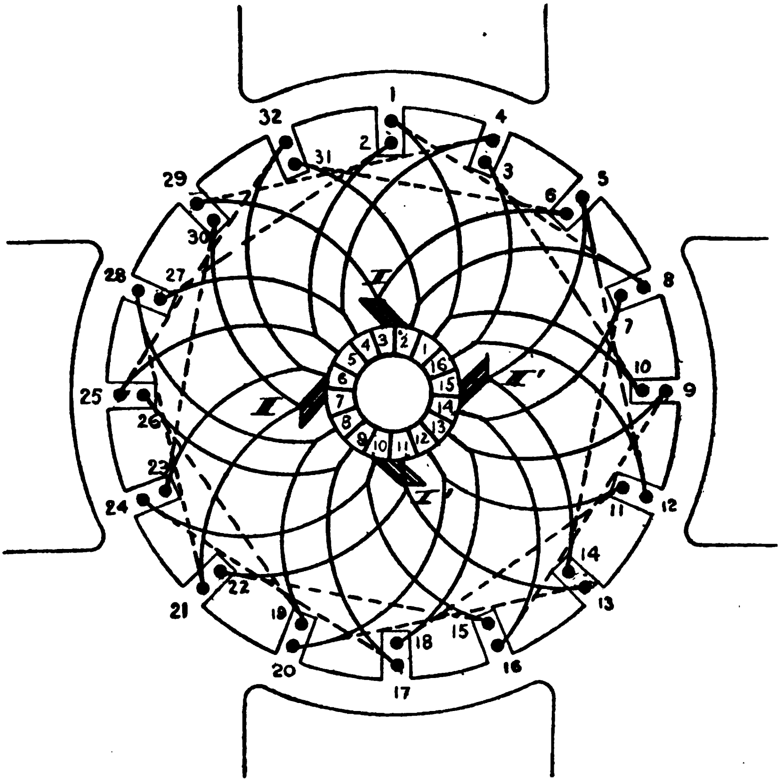


Fig. 26.—Diagram of Parallel Winding (Slotted, Hand-wound Armature), with N = 32, $y_1 = +9$, $y_2 = -7$.

Example IV

Four-pole, former-wound slotted armature. $N = 48$, $2p = 4$, $K = 24$, $b = +4$.

$$y_1 = \frac{48 + 4}{4} + 2 = 15, \qquad y_2 = \frac{48 + 4}{4} = 13$$

The diagram for this winding is shown in Fig. 27.

With a multipolar parallel winding, the conductors of one armature section are always under the influence of two consecutive poles only. Taking, for instance, the example of a four-pole armature, two of the armature sections will be under the influence of one pair

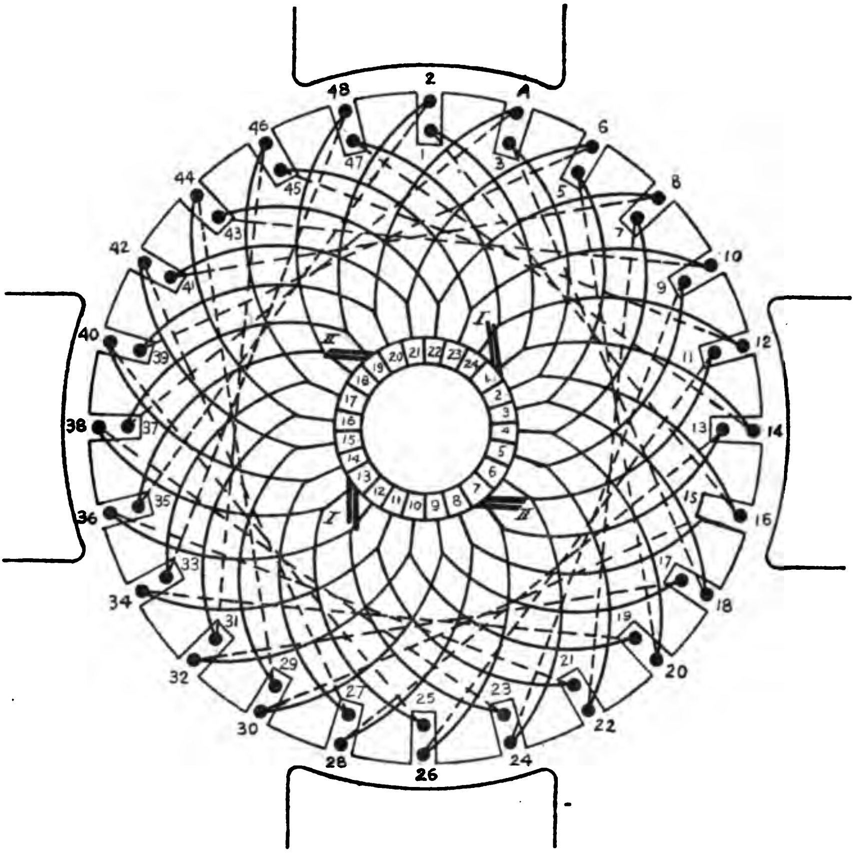


Fig. 27.—Diagram of a Parallel Winding (Slotted, Former-wound Armature), with N = 48, $y_1 = 15$, $y_2 = -13$.

of poles, while the two other sections will be under the influence of the second pair of poles. Should it now happen that the strengths of the two pairs of poles differ only very little from each other (the cause of this may be either blow-holes in one of the field-magnets or a slightly eccentric position of the armature, etc.), then the E.M.F. induced in one section of the armature will obviously differ from that induced in the other section. Since, now, all the sections are connected in parallel, an equalizing current will flow through the armature and the brushes. This current will, on account of the low armature resistance, be comparatively large, and will cause ohmic losses in the armature and sparking at the brushes.

In order to avoid these troubles, equipotential connections may be used. As the name indicates, all commutator sections of equal potential (or, what is the same, of similar relative position with regard to the magnetic field) are connected together. The equalizing currents flow then no longer through the armature and the brushes, but through these equalizing wires.

EXAMPLE V

Armature with equipotential connections. $N = 24$, $2p = 6$, $K = 12$, $b = -6$.

$$y_1 = \frac{24 - 6}{6} + 2 = 5, \qquad y_2 = \frac{24 - 6}{6} = 3$$

The diagram of connections for this winding is shown in Fig. 28. It is not necessary to cross-connect all the commutator sections; in the case of large machines

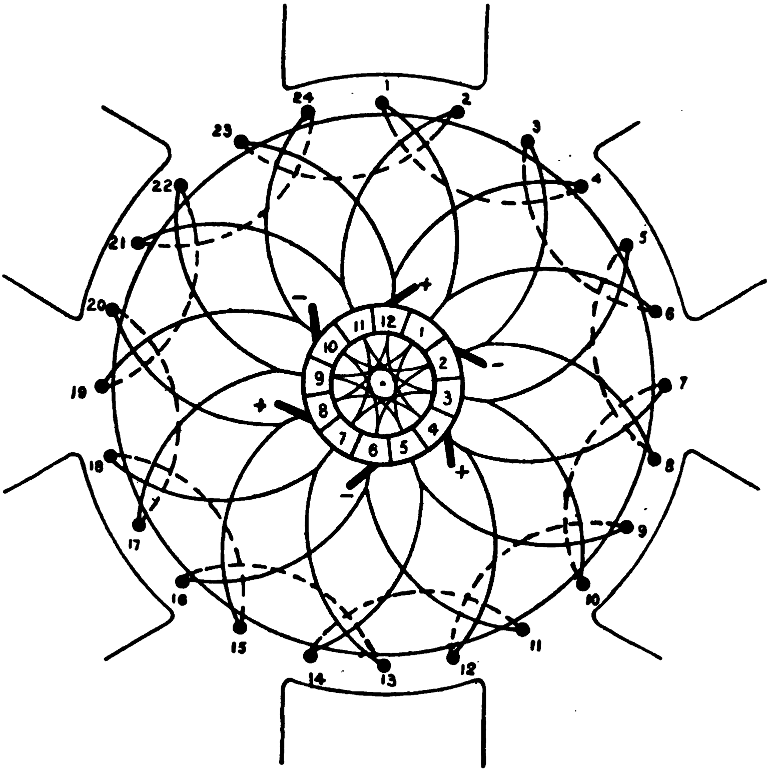


Fig. 28.—Diagram of Parallel Winding with Equipotential Connections.
N = 24, $y_1 = +5$, $y_2 = -3$.

it would be sufficient to connect $\frac{1}{2}$, $\frac{1}{3}$, or even fewer sections with each other.

(*b*) SERIES WINDINGS

In a series winding half of the armature sections are connected in series, and the two halves are connected in parallel. Thus, with a series winding, "*a*" is always equal to 1 and independent of the number of poles.

A series winding must always be a wave winding.

With regard to the pitch the following conditions must be fulfilled:—

$$y = y_1 + y_2 = \frac{N \pm 2}{p} \quad . \quad . \quad . \quad (7)$$

$$y_k = \frac{K \pm 1}{p} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (8)$$

$$K = \frac{N}{2} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (9)$$

y_1 and y_2 must be odd numbers; N must therefore always be such a number that $\frac{N \pm 2}{p}$ becomes an even number. y_1 and y_2 may either be equal to or different from each other; the former is commonly the case.

The number of collecting points on the commutator may be 2 for any number of poles, but may always be increased to $2p$.

The current flowing through each conductor is always one-half of the total current; thus—

$$c_1 = \frac{C}{2}$$

The greatest possible potential difference between two consecutive winding bars is equal, or nearly equal, to the terminal voltage of the machine.

y_k and K must not have a common factor.

EXAMPLE VI

Six-pole series-wound armature. $N = 64$, $2p = 6$, $K = \frac{N}{2} = 32$.

$$y = y_1 + y_2 = \frac{64 \pm 2}{3}$$

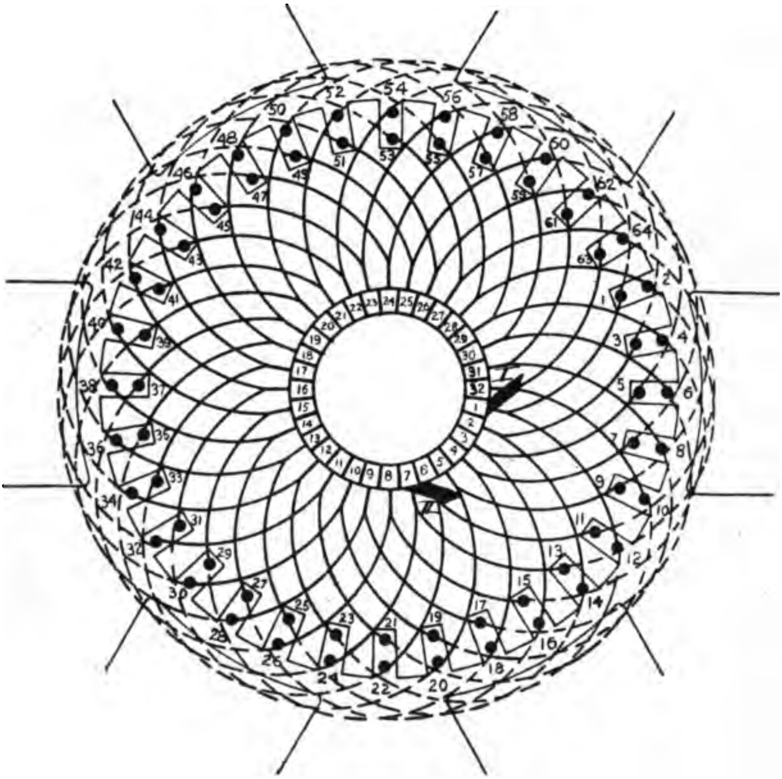


FIG. 29.—Diagram of Series Winding. $N = 64$, $y_1 = 11$, $y_2 = 11$.

We must take +2, since for −2, y would not become a whole number.

We get thus, $y = 22$, and make $y_1 = y_2 = 11$.

The diagram for this winding is shown in Fig. 29. The following table indicates the paths of the current in the armature winding. It will be seen that there are two circuits in parallel, each of these circuits consisting of three series-connected armature sections.

Brush I < 12—23—34—45—56—3—14—25—36—47—58—5—16—27—38—
1—54—43—32—21—10—63—52—41—30—19—8—61—50—39—28—17—
49—60—7—18—29—40—51—62—9—20—31—42—53—64—11 > Brush II
6—59—48—37—26—15—4—57—46—35—24—13—2—55—44—33—22

As mentioned above, y_1 and y_2 may differ from each other. In the following an example is given for this case.

EXAMPLE VII

Four-pole series-wound armature. $N = 38$, $2p = 4$, $K = 19$.

$$y = y_1 + y_2 = \frac{38 \pm 2}{2}$$

We take +2, though the winding would also be a possible one with −2. Hence

$$y_1 + y_2 = 20$$

We may now either make $y_1 = 9$ and $y_2 = 11$, or $y_1 = 7$ and $y_2 = 13$. We select the latter pitch, and have then—

$$y_1 = 7, y_2 = 13, y_k = 10$$

This winding is shown in Fig. 30. Its characteristic feature is (like that of a parallel winding with a shortened pitch) that the currents flowing in the wires between the short-circuited bars are of opposite direction; the resultant magnetic action of these wires (in Fig. 30 it is wire 5 and 6, 15 and 16, 25 and 26, and

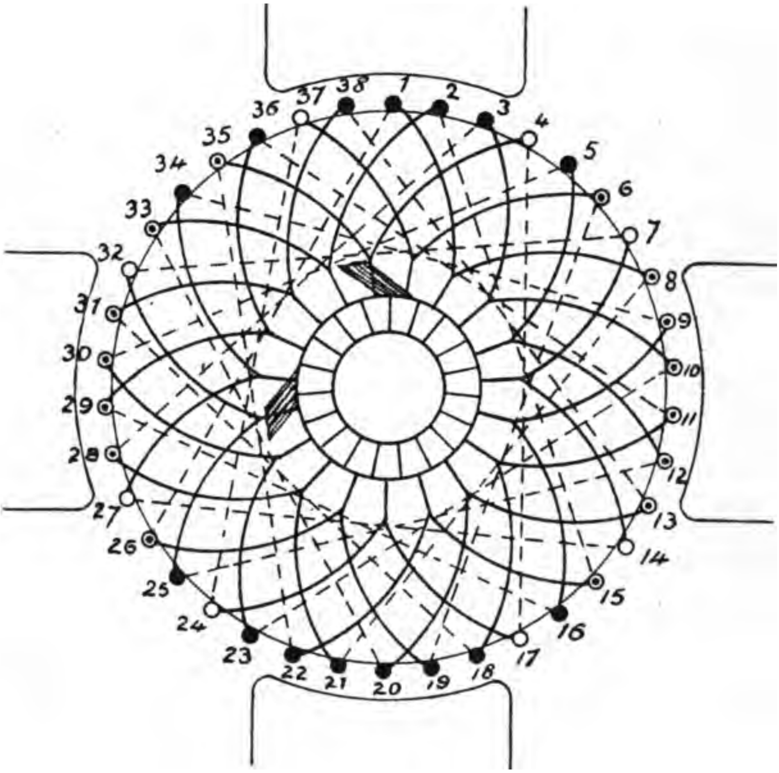


Fig. 30.—Four-pole Series-wound Armature. $N = 38$, $2p = 4$, $K = 19$, $y_1 + y_2 = 20$.

33 to 36) is zero. This winding has, therefore, the advantage of a smaller armature reaction. It has, however, several disadvantages, which nearly compensate the above-mentioned advantage. Amongst the

disadvantages are the following: a small commutating zone and a smaller mutual self-induction of the short-circuited coils, owing to the latter not being situated in the same slots.

As mentioned already, it is more usual with these windings to make $y_1 = y_2$.

With armatures for higher voltages the number of commutator sections must be made sufficiently large in order that the voltage between two consecutive sections shall not exceed a certain amount. (From 6 to 12 volts, according to the size and voltage of the machine.) With the usual windings there are generally two winding bars in one slot (see Fig. 29), so that the number of slots is equal to the number of commutator sections. With small machines this would sometimes give an unsatisfactory arrangement, as the insulation for so many slots would take up an excessive part of the available winding space. In such cases the number of slots may be reduced by placing more than two bars—say, for instance, four or six—in one slot. This winding is commonly used for former-wound high-voltage armatures, and is otherwise quite similar to that of an ordinary series-winding.

As an example of this winding we may take a four-pole former-wound armature with 102 winding bars (or former sides). The corresponding number of commutator sections is 51. By placing 2 former sides in one slot, we should get 51 slots, which in the case of a small machine may be excessive. We may, however, reduce the number of slots to one-third, *i.e.* 17.

We get then, with the same number of commutator sections, 6 former sides per slot. This winding has also the advantage of a high mutual self-induction of the short-circuited coils.

(*c*) SERIES-PARALLEL WINDINGS

We have seen that with a parallel winding the number of armature sections in parallel is equal to the number of poles, while with a series winding it is always equal to 2. It may now happen that for some particular design neither of the two cases is suitable.

The armatures of small machines are generally wire-wound, while for big armatures bar windings should be used, the advantages of the latter over the former being as follows: better mechanical construction of the winding, saving of winding space (the insulation of many thin wires takes up more space than that of few thick bars), and an easy replacement of damaged coils. For this reason, it will be found, parallel windings are generally not suitable for big machines; the current per conductor is too small, and thus the conductors too thin. If, in such a case, we try to use a series winding, we may find that the current per conductor becomes too large, and consequently the number of wires and commutator bars too small.

An example will illustrate this best. Supposing that we had to design the winding of a 14-pole dynamo, where $C = 840$. With a parallel winding the current per conductor would be $\frac{840}{14} = 60$. This current would be too small for a bar winding, since, assuming a current density of 4 amps. per square millimetre, the cross-sectional area of the conductor would be only 15 square millimetres. If, on the other hand, a series winding be selected, the current per conductor would be $\frac{840}{2} = 420$, which, apart from being too large for one bar, would reduce the number of commutator bars below the permissible limit.

In such a case the *series-parallel* winding may be used. The characteristic feature of this winding is, that the number of armature sections in parallel may be larger than two, but smaller than the number of poles. Thus, for the machine mentioned above, we could make $2a = 2$ (series winding), 4, 6, 8, 12, or 14 (parallel winding). About 150 amps. being the most suitable current per conductor for this machine, we should make $2a = 6$.

It will be seen from the above explanation that the series-parallel winding is most suitable for large multipolar machines. It has been devised by Professor Arnold, and is very extensively used in modern machines.

For series-parallel windings we have—

$$y = y_1 + y_2 = \frac{N \pm 2a}{p} \quad . \quad . \quad . \quad . \quad (10)$$

$$y_k = \frac{K \pm a}{p} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (11)$$

$$K = \frac{N}{2} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (12)$$

y_1 and y_2 must be odd numbers; N must therefore be selected so that $\frac{N \pm 2a}{p}$ is an even number ; y_1 may be either equal to or different from y_2; the former is commonly the case.

The number of collecting points on the commutator must be equal to the number of armature sections in parallel ($2a$).

Before giving some examples of series-parallel windings, it will be necessary to explain briefly the meaning of the following terms :—

1. *Symmetrical and Asymmetrical Windings.*—If the numbers of active-conductors in the different armature sections differ from each other, the E.M.F.'s induced in these sections will not be equal, which involves a certain disadvantage. In designing a winding, care should, therefore, be taken to make the winding symmetrical, if possible. Since the total number of armature sections is equal to $2a$, and the number of inducing bars is N, we may say—

A winding is symmetrical, if the number of inducing bars (N) is divisible by the number of armature sections ($2a$), or if K is divisible by a; it can be easily shown that the winding is also a symmetrical one if $\frac{p}{a}$ is a whole number.

2. *Singly and Multiply Re-entrant Windings.*—An armature winding is said to be singly re-entrant if it closes itself (or returns to its beginning) after having made one passage through all the coils arranged round the armature core. This will be explained by Fig. 31,

where for the sake of simplicity a ring winding is shown. Apart from being singly re-entrant, an armature may,

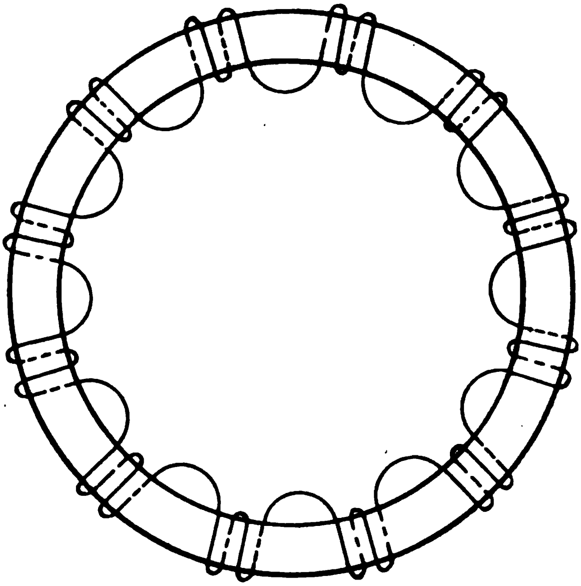


FIG. 31.—Singly Re-entrant Ring Winding.

of course, have either two, or any larger number of armature sections in parallel.

An armature winding is doubly re-entrant if it only re-enters itself after having made two passages round the coils of the armature. Fig. 32 serves as illustration for such a winding. Starting from any point, for instance A, it will be seen that we have to go twice round the armature before we return to A, and all the wires are connected up.

In the same way a winding may be trebly or multiply re-entrant.

The symbols generally used for indicating the re-entrancy of a winding are—

○ for a singly re-entrant winding.
◎ for a doubly re-entrant winding.
⊚ for a trebly re-entrant winding, etc.

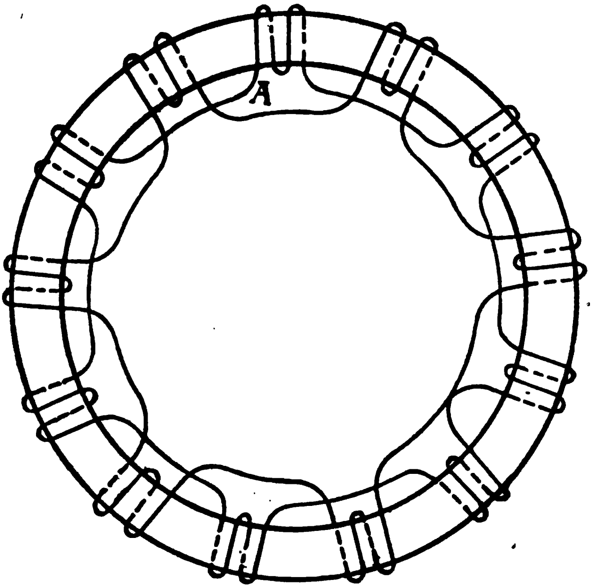


Fig. 32.—Doubly Re-entrant Ring Winding.

3. *Simplex, Duplex, or Multiplex Windings* (Single, Double, or Multiple closed Windings).—An ordinary Gramme winding, such as shown in Fig. 31, is called a simplex or singly-closed winding, because it consists of one single winding, which is closed in itself. Apart from being a simplex winding, it may be either singly or multiply re-entrant. For instance, Fig. 32 shows a simplex, doubly re-entrant winding.

An armature may, however, be wound with two independent circuits, each of which may be singly or multiply re-entrant, and is then called a duplex, or doubly-closed winding. Fig. 33 shows a duplex singly re-entrant winding; it consists of two absolutely independent windings, which are distinguished from each other by full and dotted lines respectively. Such an armature might be provided with two separate commutators (one on each side of the armature), or one commutator may be used and the number of sections doubled, the two sets of sections being alternated between each other. In this case the brushes must be wide enough to cover simultaneously at least 2½ commutator sections, so as to collect from both windings simultaneously.

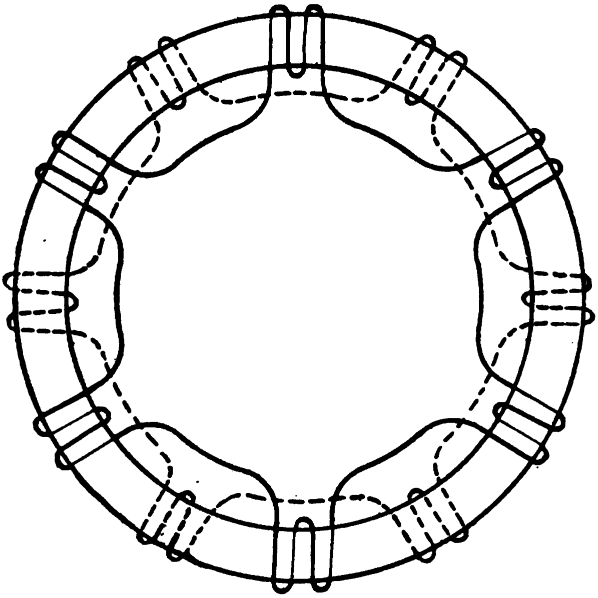


FIG. 33.—Singly Re-entrant Duplex Winding.

With regard to the number of armature circuits in parallel, it is obvious that in a duplex winding this number is twice as great as it would be were the same armature simplex-wound.

An armature with three entirely independent windings would be called triplex wound, and the number of armature circuits in parallel would be three times that of a corresponding simplex winding.

Generally, if we call m the number of independent circuits on a multiplex winding, and $2a$ the number of armature circuits in parallel on each of these m independent windings, then the total number of circuits in parallel will be $2am$.

Whether an armature is simplex or multiplex wound depends entirely on the ratio of y_k and K, or y_k and a; if y_k and K have no common factor, the winding is simplex. If the common factor of y_k and K is 2, the winding is duplex, or, generally, if the common factor of y_k and K is m, the armature is m-plex wound or m-fold closed.

The following symbols are commonly used :—

o for a simplex-wound armature.
oo for a duplex-wound armature.
ooo for a triplex-wound armature, etc.

To return now to the series-parallel winding, two important conditions should always be fulfilled, viz. :—

1. The winding should be a symmetrical one, *i.e.* $\frac{p}{a}$ should be a whole number.

2. If the total $\frac{p}{a}$ is not a whole number, the winding should consist of as many independent windings as to make $\frac{p}{a}$ a whole number for each of the independent windings.

An example will explain these conditions better. Supposing that with a twelve-pole armature we wish to make $2a = 8$; the winding, if made as a simplex winding, would not be symmetrical, since $\frac{p}{a}$ would not be a whole number. If, however, we select a duplex winding, then for each of the two independent windings $2a$ must be equal to 4, and $\frac{p}{a}$ would be a whole number for each of the two independent windings. The same would be the case for $m = 4$ (quadruplex winding), as $2a$ would be equal to 2 for each independent winding, and $\frac{p}{a}$ would be a whole number, viz. 6.

Another example. For the same machine ($2p = 12$) we wish to make $2a = 14$. This would not give a symmetrical winding; the only possible winding is here one with $m = 7$, hence $2a = 2$ per independent winding. This would give $\frac{p}{a} = 6$.

If the above conditions 1 and 2 are observed, $\frac{K}{a}$ will always be a whole number; thus a series-parallel winding should always be so designed that $\frac{K}{a}$ is a whole number.

Experience has shown that in the case of large machines provided with series-parallel windings it is of advantage to make equipotential connections. In such a case it is, however, quite sufficient to connect every fourth or eighth commutator section.

EXAMPLE VIII

Eight-pole armature, slotted, former-wound. $N = 76$, $2p = 8$, $2a = 4$, $K = 38$.

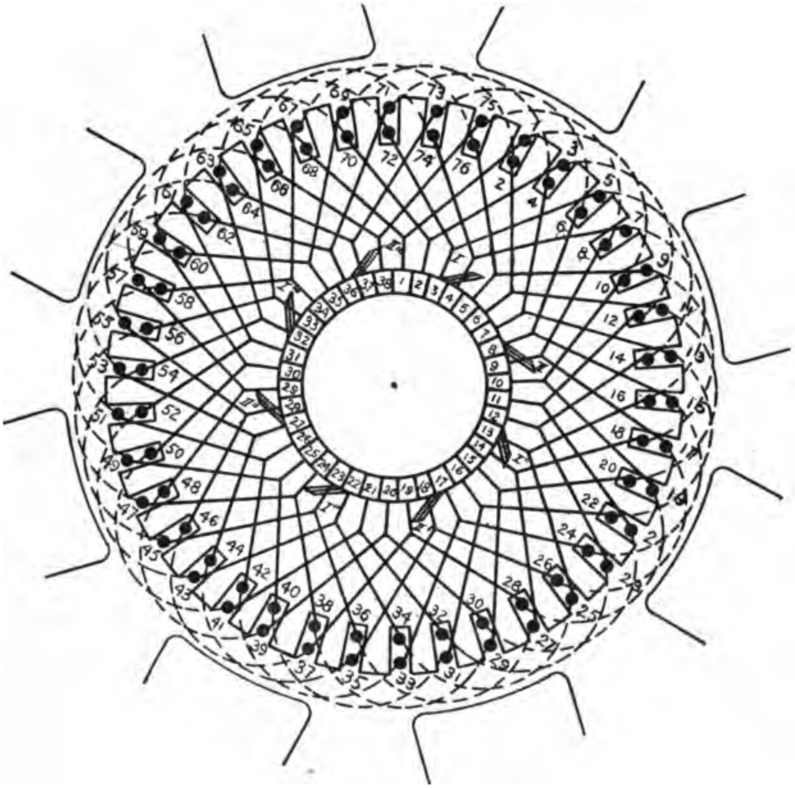
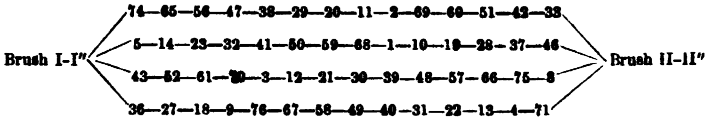


FIG. 34.—Eight-pole Armature. $N = 76$, $2p = 8$, $2a = 4$, $K = 38$, $y_1 = y_2 = 9$, $y_k = 9$.

$$y_1 + y_2 = \frac{76 - 4}{4} = 18, \; y_1 = y_2 = 9, \; y_k = \frac{38 - 2}{4} = 9$$

This is apparently the simplest case of a series-parallel winding; $\frac{p}{a}$ being a whole number, the armature may be simplex-wound.

Fig. 34 shows the diagram for this winding, while the following table indicates the path of the current in the armature :—



Example IX

Ten-pole series-parallel armature, slotted, former-wound. $N = 144$, $2p = 10$, $2a = 6$, $K = 72$.

Since $\frac{p}{a}$ is not a whole number, the armature cannot be simplex-wound. The smallest value of m that will satisfy this condition is 3; for, $2a$ will then be 2 for each independent winding, and $\frac{p}{a}$ will be 5. The armature must thus be triplex-wound.

$$y_1 + y_2 = \frac{144 \pm 6}{5} = 30$$

We make $y_1 > y_2$, thus—

$$y_1 = 17, \text{ and } y_2 = 13,$$

$$\text{and } y_k = \frac{72 \pm 3}{5} = 15$$

Fig. 35 shows the diagram for this winding.

It is obvious that this winding cannot be designed for any number of armature conductors. If, therefore, the calculation gives an unsuitable number of wires, this must be reduced or increased to the nearest number which will fulfil the conditions for the respective winding. For instance—

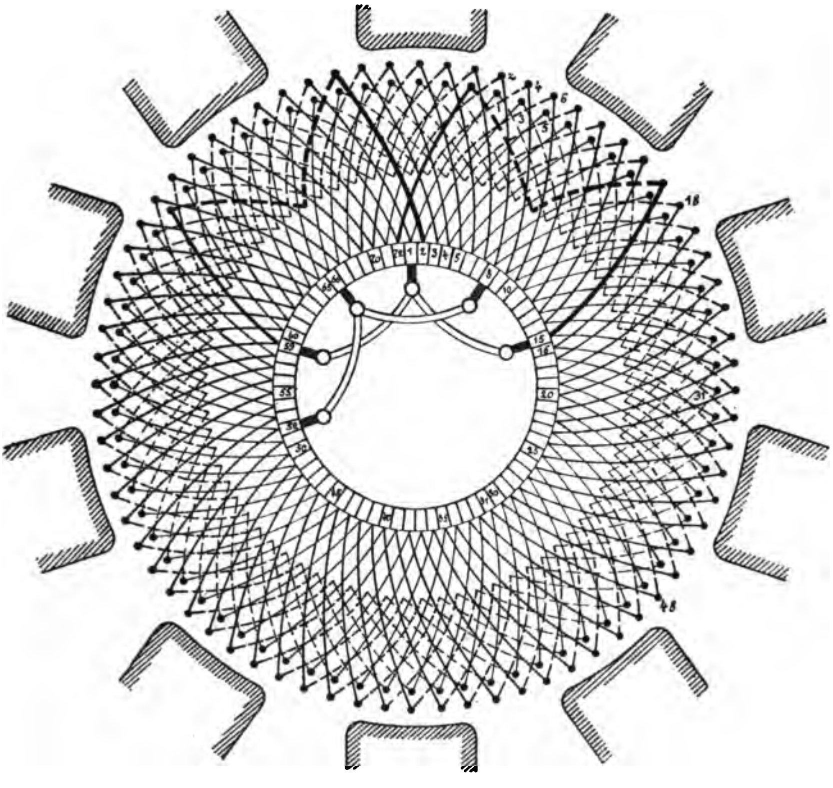


FIG. 35.—Ten-pole Series-parallel Wound Armature. N = 144, $2p = 10$, K = 72.

$$2p = 16,\ 2a = 12,\ N = 410,\ K = 205$$

$$\text{then } y_1 + y_2 = \frac{410 \pm 12}{8} = 52\tfrac{6}{8} \text{ or } 49\tfrac{6}{8}$$

The above number of conductors is, therefore, an impossible one for this winding. Supposing we increase the number of wires to 412, then

$$y_1 + y_2 = \frac{412 - 12}{8} = 50$$

gives possible values for y_1 and y_2, viz. 25.

The winding is therefore possible with 412 conductors; in this case, however, K is equal to 206, and $\frac{K}{a}$ is not a whole number. The next number of commutator bars which fulfils this condition is 210, and the corresponding number of conductors N = 420.

Since—

$$y_1 + y_2 = \frac{420 + 12}{8} = 54$$

this number of conductors fulfils all conditions. The winding will be a symmetrical one with $m = 3$ (triplex winding).

It will be easily seen that by inserting into formulæ (10) and (11) the corresponding values for $2a$, the series-parallel winding may be transformed into either a parallel winding or a series winding. In this way we may design a parallel winding as a wave instead of a loop winding, and thus avoid the disadvantages of a pure parallel winding (see p. 26).

CHAPTER II

THE CONSTRUCTION OF DRUM WINDINGS

1. Hand Windings

HAND windings are commonly used for small two-pole armatures only. They are too expensive to manufacture, have an ugly appearance, and do not admit a ventilation of the side connections. In the case of a breakdown of one of the lower coils the whole winding has sometimes to be taken off before the damaged coil can be got at.

Hand windings are generally made after the diagram Fig. 36. The armature has in this example fourteen slots and fourteen coils, each consisting of three turns, so that there are two winding bars in each slot, each of which consists of three conductors. The number of winding bars per slot need not be just two, but may, as explained on page 13, be any multiple of 2. Two or four bars per slot is, however, most suitable for hand windings.

In Fig. 36 the beginning and end of each coil is numbered. Thus the beginning of the first coil is marked " 1," the end of it " 1′," etc. The coils are first wound in the order as indicated by the Roman figures I–VII. Thus coils 1 and 8 are wound first into slots 1 and 8. Next coils 4 and 11 are wound into slots 4 and

11, then coils 6 and 13 are wound into their respective slots, etc., until finally coils 3 and 10 are wound.

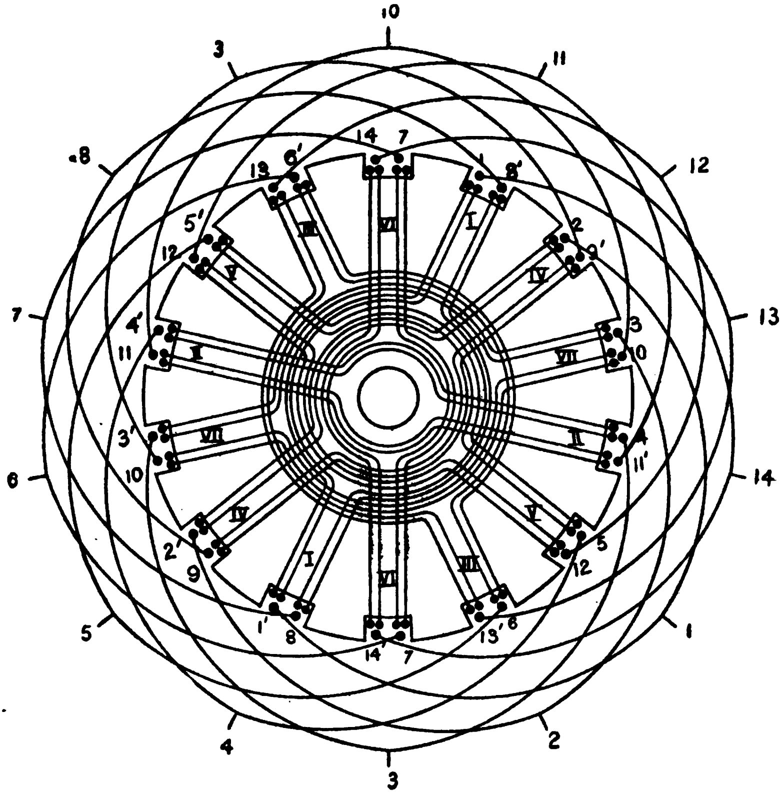


Fig. 36.—Diagram for Two-pole Hand-wound Armature.

The ends of the coils are first of all left open, and after all the coils have been wound on the armature, the end of each coil is joined with the beginning of the next one and the corresponding commutator bar. For instance, 1', being the end of coil 1, is joined with 2, being the beginning of coil 2, and the corresponding commutator bar 1; in this way all the ends are joined with each other and with the commutator bars.

Besides the slot insulation and the insulation between any two coils, the sides of the windings must also be properly insulated. This is commonly done by covering the sides of each coil with a sheet of insulating material immediately after it has been wound. For instance, after coils 1 and 8 have been finished, their side connections are covered with an insulating sheet, on which then the side connections of the next set of coils are laid, which in turn are insulated in the same manner, etc. Obviously this insulation takes up much space, and prevents the air from reaching and cooling the end connections.

In order to find the distance that should be kept between the ends of the armature and the commutator and bearing respectively, it is necessary to determine the area, A, of the winding space required for the side connections (see Fig. 37).

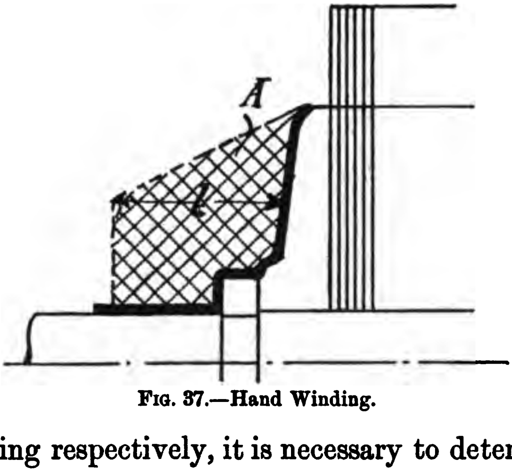


Fig. 37.—Hand Winding.

Let a_i be the area of each conductor, including insulation, in square millimetres, and Z the total number of conductors on the armature; then

$$A = CZa_i \quad . \quad . \quad . \quad . \quad (13)$$

where C is a constant, depending on the size and voltage of the machine.

From the winding area A thus formed the length l between the armature sides and the commutator and bearing can easily be estimated.

In the following table are given a few approximate values for the constant C :—

Voltage.	Size in KW.	Constant C.
Up to 150	Up to 1	1·4
Up to 500	Up to 1	1·6
Up to 150	Up to 5	1·3
Up to 500	Up to 5	1·5

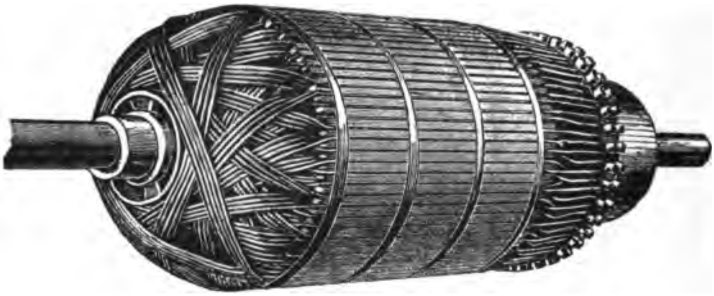


FIG. 38.—Hand-wound Armature.

Fig. 38 shows a complete hand-wound armature which is wound after the diagram in Fig. 36.

2. Bar Windings

With large machines for low and medium voltages the number of conductors becomes comparatively small, and their cross-sectional area correspondingly large. It is then no longer possible to use wire conductors, but solid bars of either square or rectangular cross-section must be employed. These bars are either drawn through slots, as is commonly the case, or otherwise arranged on the circumference of the armature.

The connections between these conductors may either be turned down in evolutes, and thus placed at the sides of the armature (this type of winding is called "Evolute Winding"), or the conductors may be carried out in the cylindrical surface and bent to meet obliquely in two overlapping layers (such a winding is called a "Barrel Winding").

These two types of bar windings will now be described.

(*a*) Evolute Windings

The characteristic construction of this winding is shown in Figs. 39 and 40. It consists of the bars or conductors N_1 and N_2 and the V- or evolute-shaped connectors C_1 and C_2; it may be grouped either as lap winding, as shown in Fig. 40, or as wave winding, shown in Fig. 39. One of the evolute bent strips is always bent inwardly, the other one outwardly, and their outer ends are usually soldered on to the conductors.

It is clear, therefore, that with two bars per slot the conductors must be alternately long and short. The longer conductor should always lie above the short one in the slot.

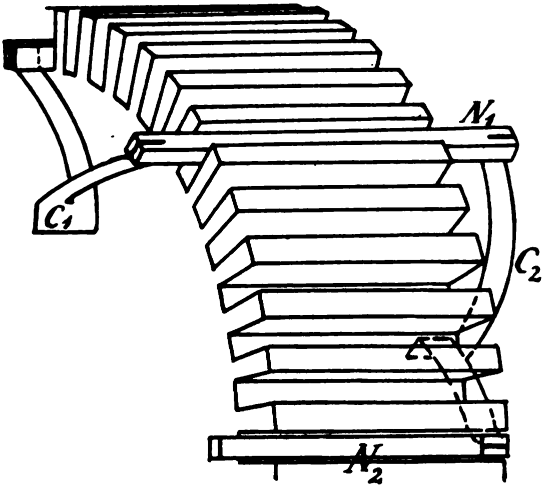


Fig. 39.—View of Evolute Winding, Wave Grouping.

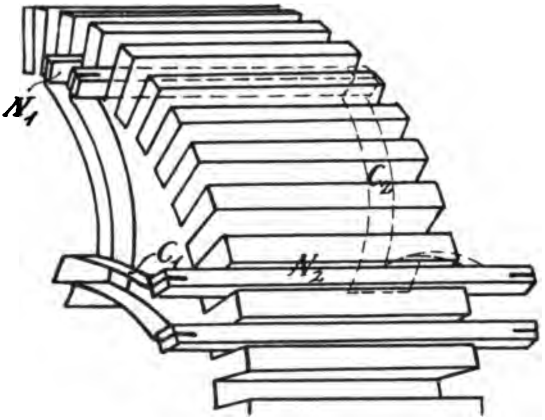


Fig. 40.—View of Evolute Winding, Lap Grouping.

The construction of the evolute for the connecting strips is shown in Fig. 41. The radius *r* should be made as large as possible.

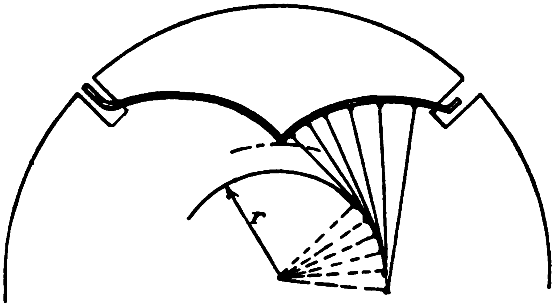


Fig. 41.—Construction of Evolute.

A simple construction of an evolute winding is shown in Fig. 42. The bars and the strips are here cut out of one copper sheet, are bent into shape, and then connected by means of a short copper strip *S*; the latter is soldered or otherwise connected with the corresponding commutator section.

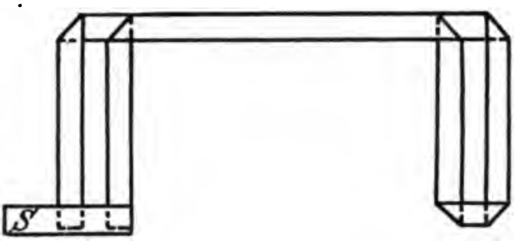


Fig. 42.—Evolute Winding; Section consisting of Bent Strip.

In large machines it is usual to anchor the middle part of each evolute to an insulated clamping device, built up like a commutator, and sometimes called a "false commutator." This method of construction is shown in Fig. 43. It will be noticed that this winding consists of

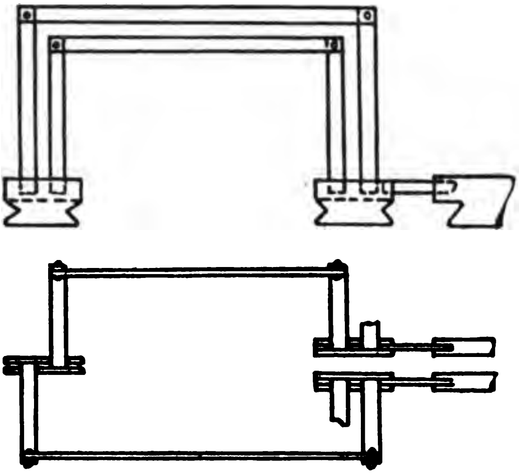


FIG. 43.—Evolute Winding; Section consisting of Eight Pieces.

no less than eight parts, viz. the two conductors, four side connectors, and two clamping pieces, which are shaped like commutator bars, and insulated from each other by means of strips of presspahn, mica, etc. The conductors and side connections are riveted and soldered together.

Fig. 44 shows a complete armature provided with evolute winding.

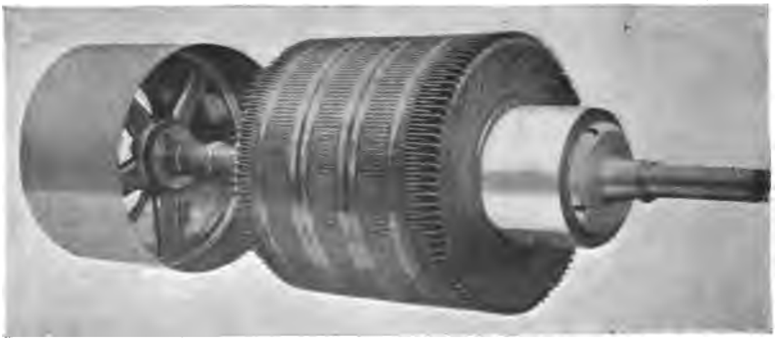


Fig. 44.—Armature with Evolute Winding.

(*b*) BARREL WINDINGS

The characteristic feature of the barrel winding is that the conductors, instead of being turned down in evolutes, are carried out in the cylindrical surface, and bent to meet obliquely in two overlapping layers.

This winding, too, may be grouped as wave or lap winding, as will be seen from Figs. 45 and 46. Its main disadvantage is that it makes the total length of the armature greater; on the other hand, the wires are perfectly free, and their ventilation and cooling are excellent. The armature is usually provided with projecting brackets at the ends to support the winding.

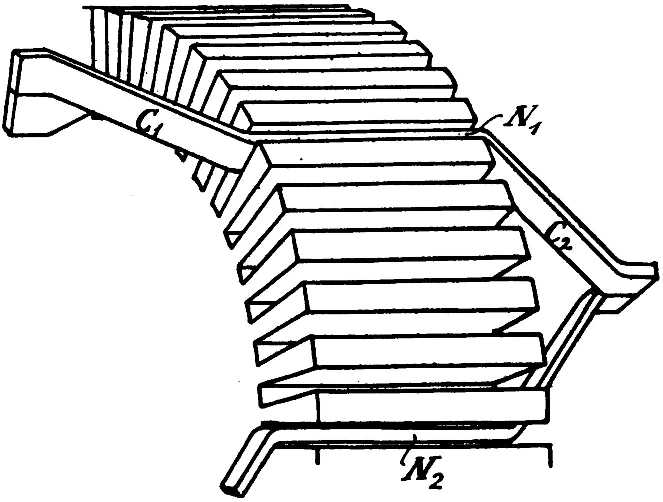


FIG. 45.—Barrel Winding, Wave Grouping.

The simplest construction of a barrel winding is shown in Fig. 47. A copper strip is first bent over its edge and then into the proper shape. The dotted line in Fig. 47 indicates the shape of the copper strip for a

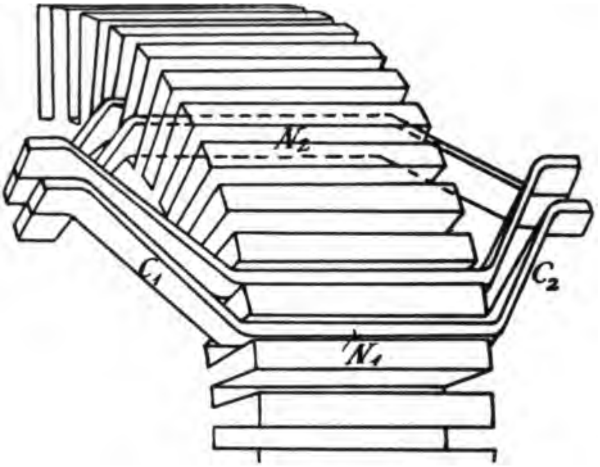


Fig. 46.—Barrel Winding, Lap Grouping.

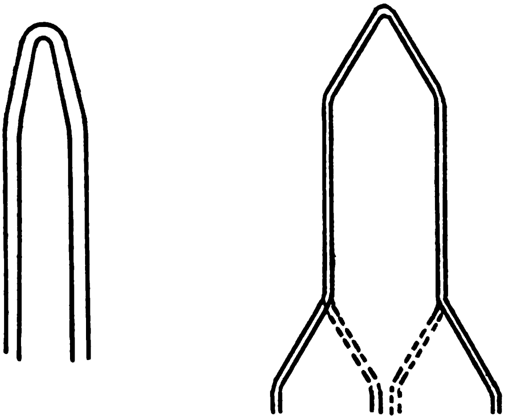


Fig. 47.—Section of Barrel Winding (Bent Strip).

lap winding, the full line for a wave winding. Another, more elaborate construction, is shown in Fig. 48. This winding consists of two bars, I and II, which are held together by metal clips.

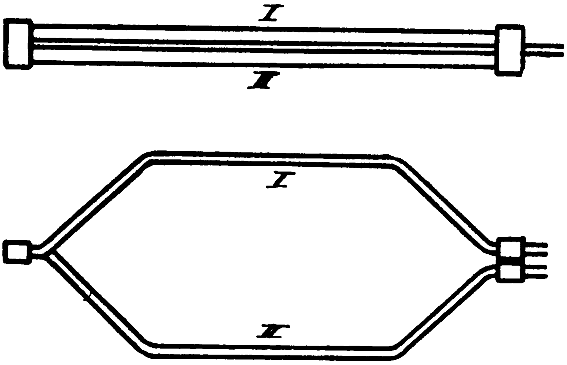


Fig. 48.—Section of Barrel Winding.

A combination of the barrel and the evolute winding is shown in Fig. 49. On one side evolute-shaped strips are used, on the other side the bars are bent into shape for the side connections.

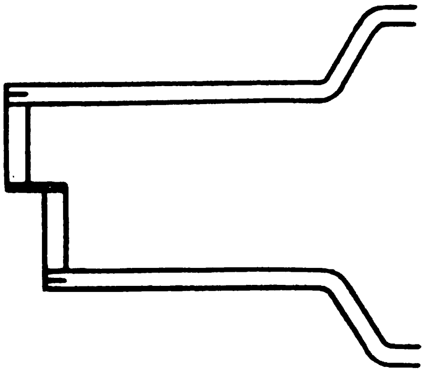


Fig. 49.—Section of Barrel-evolute Winding.

In all constructions, in which each winding element consists of several pieces (as in the constructions shown in Figs. 45, 46, 48, and 49), it is of extreme importance that both the electrical and mechanical connection between the bars and the side connectors should be as perfect as possible. Thus the conductors and side connectors should not only be riveted together, but, wherever possible, they should also be soldered. Imperfect joints may not only cause a great ohmic loss, and consequently excessive heating of the armature, but may, as has been mentioned already, give rise to excessive sparking (internal currents).

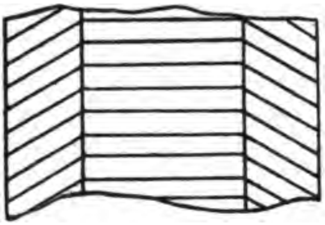


Fig. 50.—Loop Winding.

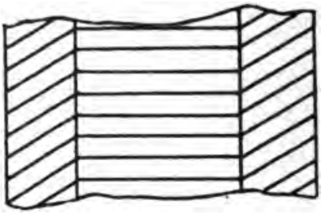


Fig. 51.—Wave Winding.

Whether a barrel-wound armature is lap- or wave-grouped is easy to tell from a glance at the winding of the finished armature. In the former case both the side connections from one conductor are running in the same direction, while in the latter case they run in different directions (Figs. 50 and 51).

A complete armature provided with barrel winding is shown in Fig. 52.

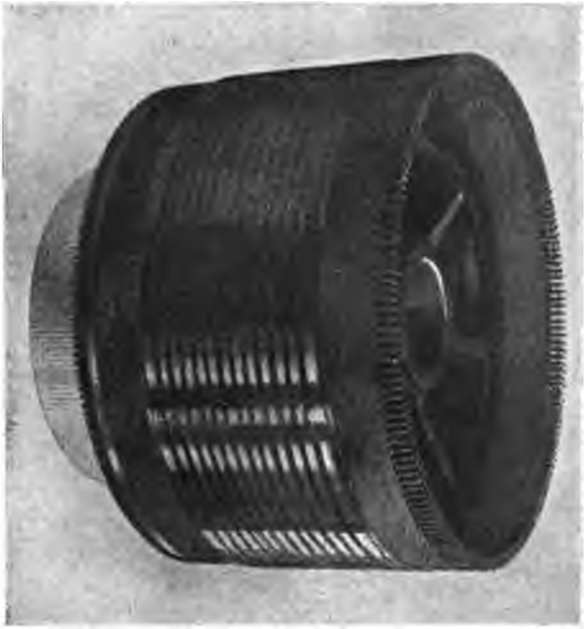


FIG. 52.—Barrel-wound Armature.

(c) FORMER WINDINGS

In these types of windings the individual coils are first wound or shaped upon a frame or former, the cotton-covered wire being first of all dried; each coil is then separately insulated, usually by winding with dry tape, baking, varnishing, and baking again. The tape is generally half lapped to avoid undue thickness. Sometimes, however, the coils are wound in a straight loop (see Fig. 53), and then brought into the proper shape either by hand or by means of shaped blocks, sometimes also by means of specially constructed bending machines.

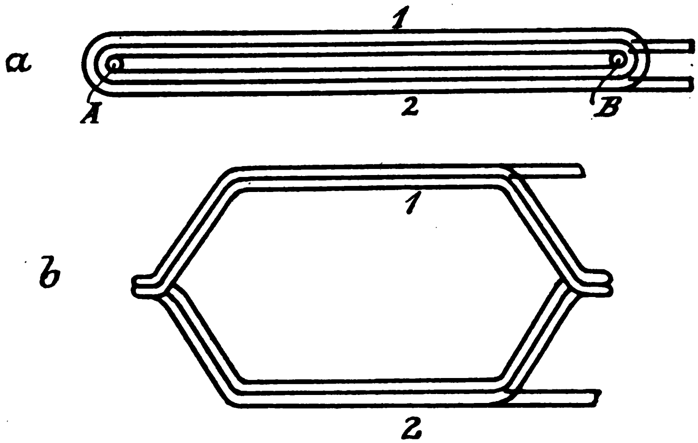


Fig. 53.—Former-wound Coil.

The finished coils may either be evolute-shaped or barrel-shaped. There are very many different methods of manufacturing these coils; a few of the typical methods will be described.

One of the simplest former windings is shown in Fig. 53. The wire is wound in several turns round two bolts, A and B, and then taken off these; it forms a simple, straight loop. Next, the two sides 1 and 2

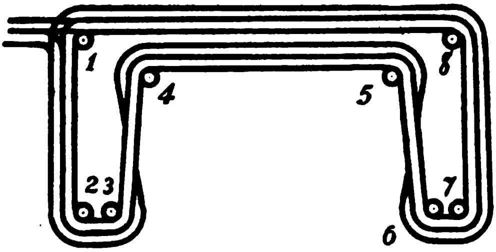


FIG. 54.—Former-wound Coil.

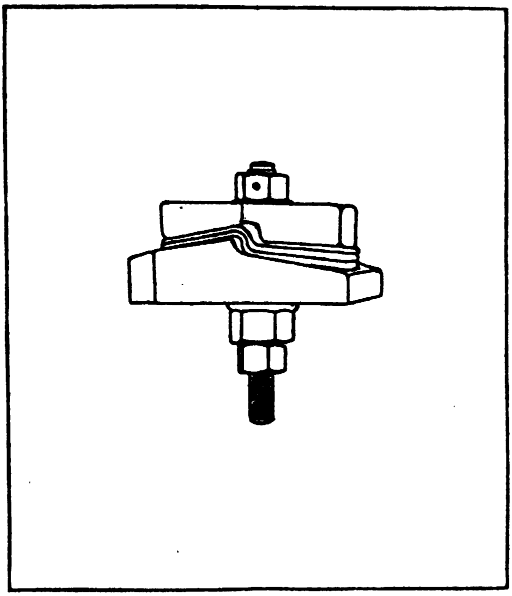


FIG. 55.—Former Block.

are clamped between two wooden blocks, and drawn from each other. In this way we get a former coil, as shown in Fig. 53, *b*; by building together these formers we get a barrel-shaped armature.

The single formers may be insulated either before or after they are bent into shape. With very small armatures it is not necessary to bend the formers into shape, but this may be done by putting the formers into the slots. Sometimes the wires are wound on a circular block; they have then the shape of a ring instead of a loop.

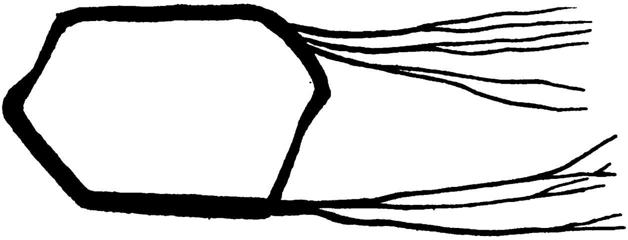


Fig. 56.—Former-wound Coil.

Another way is to wind the wire round the bolts 1–8, as shown in Fig. 54; if these formers are bent into shape and built up on the armature, they give an evolute-shaped winding.

The former coils may also be wound directly into shape, as shown in Fig. 55.

Finally, Figs. 56–59 show various-shaped former coils and complete former-wound armatures.

The former shown in Fig. 56 consists of three complete coils, each turn of which has two wires connected in parallel. Such a former is suitable for the winding described on p. 32. The complete armature wound in this manner is shown in Fig. 57.

The method of placing the formers into the slots will be clear from a glance at Fig. 58. The formers consist here of bent copper strips.

Fig. 59 shows a very large former-wound armature, the formers being made up of stout copper wires.

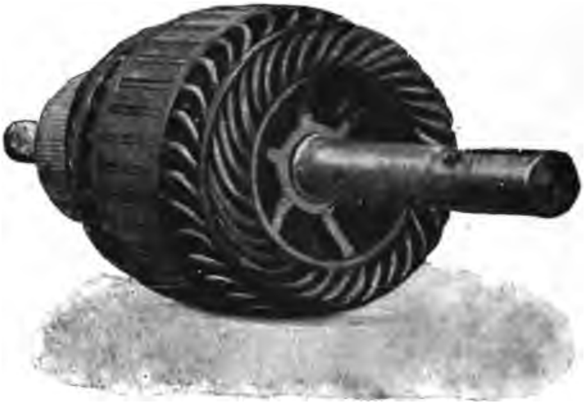


FIG. 57.—Former-wound Armature.

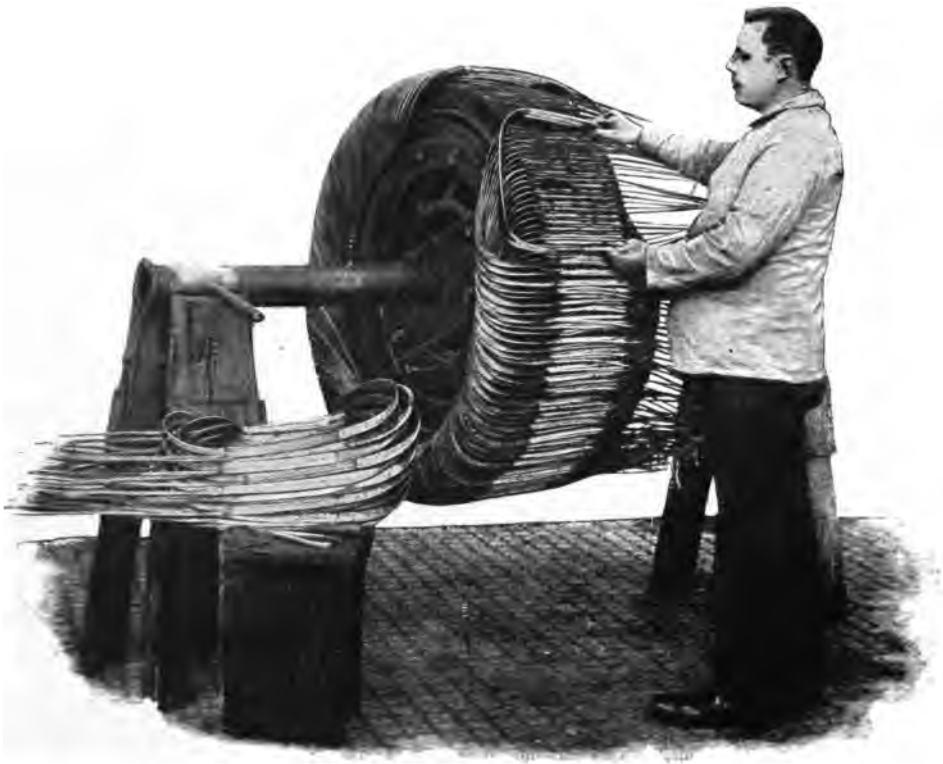


FIG. 58.—Former-wound Armature in course of Construction.

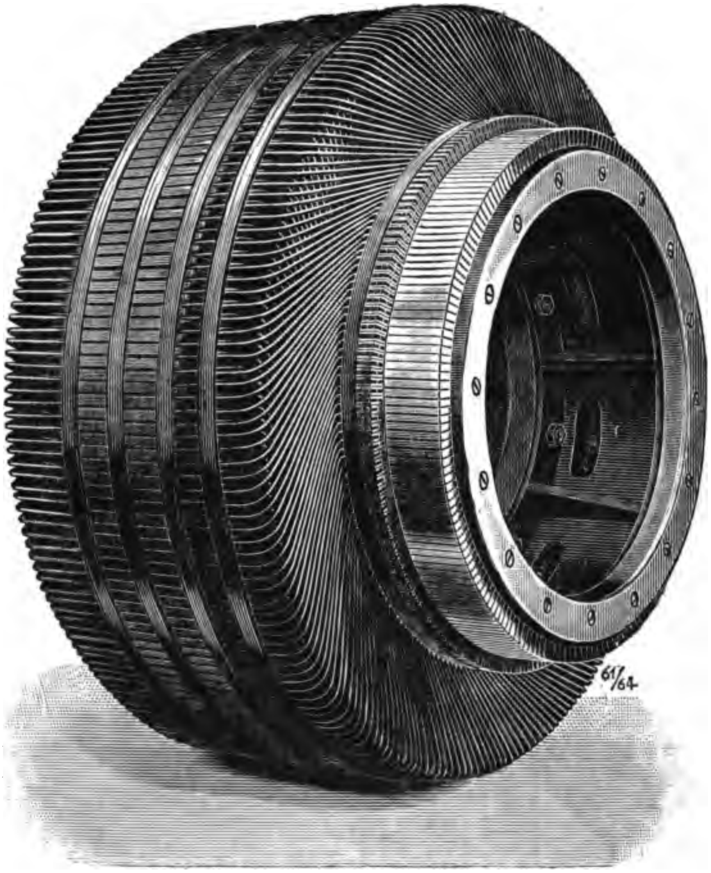


Fig. 59.—Former-wound Armature.

CHAPTER III

THE CONSTRUCTION OF ARMATURES

(*a*) THE CORE

THE core of a continuous current armature consists of a number of stampings hydraulically pressed and kept together by means of bolts and screws, or by specially fixed plates.

The stampings should be of very soft charcoal iron, the thickness of which is generally about 0·5 mm.; as the eddy current losses are proportional to the square of the thickness of the stampings and the square of the frequency, it is advisable to use thinner stampings (about 0·3 mm.) for machines the frequency of which, *i.e.* the number of pairs of poles times the number of revolutions per second, exceeds 25 to 30.

With small machines, having a diameter up to about 0·6 m., the core discs are generally stamped out of one piece. Where the armature exceeds the above diameter, it is cheaper to stamp the discs in segments and build the core up of the single segments; the latter should overlap in successive layers, as indicated in Fig. 60.

The discs must be stamped out very accurately, so that it should not be necessary to turn the outer surface after assembling the armature. Should the periphery of the armature, however, be too irregular, it may be ground over, but should never be turned. It has been found by numerous experiments that turning the periphery of an assembled armature increases the eddy current losses sometimes by as much as 30 to 50 per cent.

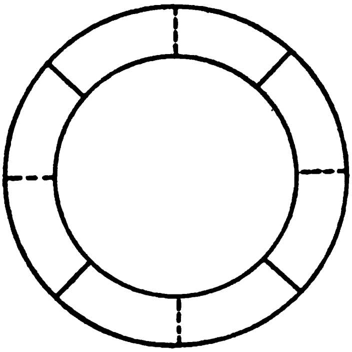


FIG. 60.—Arrangement of Disc Segments.

It is necessary to insulate the core discs from each other; this may be done by building the core up of iron and thin paper discs alternatively. Frequently the paper is pasted by machinery to the iron discs prior to stamping them out. The thickness of the paper used varies from 0·05 to 0·1 mm. Sometimes the discs are painted on one side with varnish or with waterglass enamel. It has also been found that the mere existence of a film of oxide of iron is sufficient insulation.

In the case of armatures which are turned after they are assembled, or in which the slots are not stamped, but milled out, it is advisable to insert between each thirtieth or fortieth disc a sheet of fibre or presspahn of about 0·5 mm. thickness, so as to reduce the disadvantageous effect of the turning or milling.

The effective cooling of the armature is of extreme importance. In some cases, more especially with small armatures, it is sufficient to stamp several holes into the armature, as indicated in Fig. 61. With larger armatures, however, it is necessary to provide radial ventilation ducts. To keep the core discs apart at these ventilating ducts, distance pieces must be introduced.

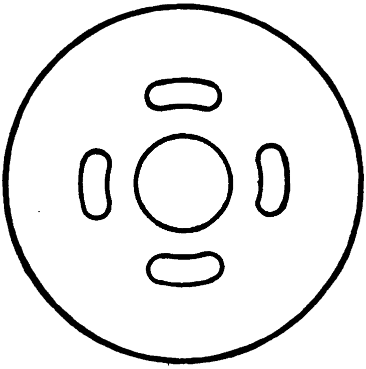


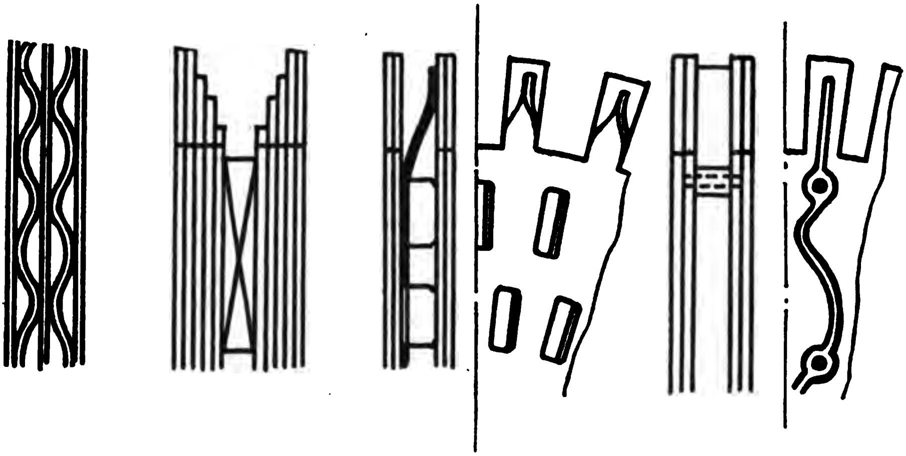
FIG. 61.—Ventilation-holes in Armature Disc.

Some such devices are shown in Figs. 62–65, and do not require any further explanation.

The ventilating ducts are generally inserted at distances of about 5 to 8 cms.

Although up to about ten years ago smooth-core armatures were in vogue, modern machines are almost exclusively provided with slotted armatures. The following are the most important advantages of slotted, compared with smooth armatures:—

(1) The air-gap may be reduced so far as is allowable with regard to the armature reaction, and thus a considerable amount of copper for the excitation may be saved.



FIGS. 62–65.—Method of construction of Ventilation Ducts in Armature.

(2) The eddy current losses in the armature conductors are considerably smaller with slotted than with smooth armatures.

(3) By making the induction at the bottom of the teeth very high, the reaction of the armature on the magnetic field is reduced; besides, an increase of the tooth induction has a similar effect on the commutation as an increase of the air-gap.

(4) The mechanical construction of the winding is much better and cheaper with slotted than with smooth armatures.

(5) Owing to the exposure of the cylindrical surface of a slotted armature, the cooling is facilitated.

Slots are generally stamped out of the single discs, and in few cases only are they milled out after the armature has been assembled.

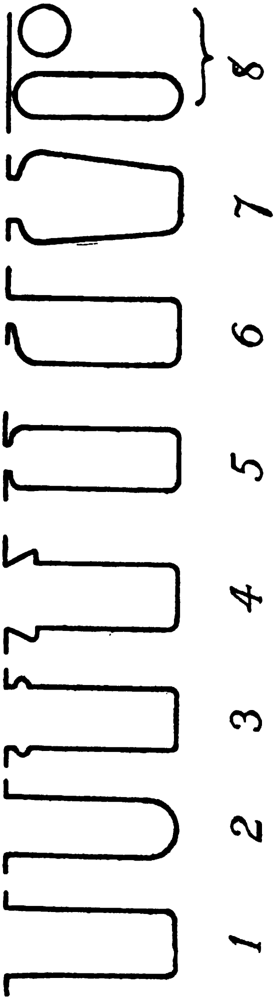


Fig. 66.—Slot Shapes.

A few of the most usual slot-shapes are shown in Fig. 66, 1–8. Nos. 1 and 2 may be either punched or milled; both are open, and therefore require binding wires to keep the armature windings in place. Nos. 3 and 4 are also open, but have grooves through which wedges may be drawn, and the slot thus closed. Though binding wires are not essential in this case, they are generally provided as an additional security. Nos. 5, 6, and 7 are partly closed. They have the advantage of securing the winding very well in its place, but offer some difficulties to the placing of the windings in the slots; more especially is this the case with former-wound coils. No. 8 shows two perfectly closed slots, which are used in exceptional cases only.

The arrangement of the windings in the differently shaped slots is shown in Fig. 67. No. 1 shows a wire winding in an open slot, No. 2 a similar winding in a partly closed slot. The winding is secured in its place by means of a wedge-shaped strip of wood. No. 3 shows a former winding in an open slot. The slot is closed by means of a strip of fibre, wood, or a similar material, over which the binding wires are wound.

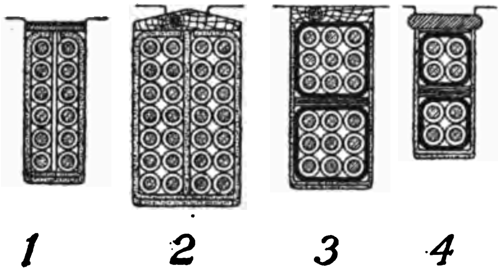


Fig. 67.—Arrangement of Wire and Former Windings in Slot.

No. 4 shows a former winding in an open slot; the winding is here again secured by a wedge, which is drawn through the grooves at the upper end of the slot.

Similar arrangements for bar windings are shown in Fig. 68, 1–3.

Before the winding (whether hand or former winding) is placed in the slots, the latter must be suitably insulated. The quality and thickness of this insulation varies, of course, according to the voltage of the machine. While for lower voltages, up to about 250, presspahn and oiled linen or paper will suffice, a layer or two of either pure mica or one of the mica compounds, such as mica cloth or mica paper, should be added in the case of machines up to 550 volts.

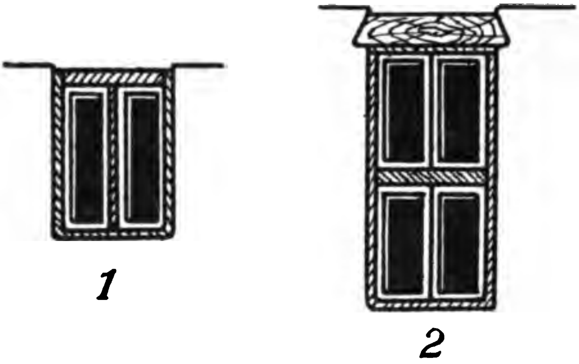


FIG. 68.—Arrangement of Bar Windings in Slot.

The following table gives details about the slot insulation which should be used for the various types of windings and different voltages :—

Type of winding.	Voltage.	Presspahn. mm.	Oiled cloth or paper. mm.	Mica, or mica compounds.	Manila paper. mm.	Presspahn. mm.	Total thickness of insulation. mm.
Hand ...	-110	0·2	0·2	—	0·1	0·2	2×0·7
Former ...		0·2	0·1	—	0·1	0·2	2×0·6
Bar ...		0·2	0·1	—	0·1	0·2	2×0·6
Hand ...	-220	0·2	2×0·2	—	2×0·1	0·2	2×1·0
Former ...		0·2	0·2	—	2×0·1	0·2	2×0·8
Bar ...		0·2	0·2	—	0·1	0·2	2×0·7
Hand ...	-550	0·3	2×0·2	2×0·2	2×0·15	0·3	2×1·7
Former ...		0·3	2×0·2	2×0·2	—	0·3	2×1·4
Bar ...		0·3	2×0·2	2×0·2	—	0·3	2×1·4
Insulation between coils or formers	-220	0·3	—	—	—	—	0·3
„	-550	0·2	—	0·1	—	0·2	0·5

The insulating materials must, of course, always be so arranged that the mechanically weak materials, such as, for instance, oiled paper and linen, manila paper, etc., are placed between the mechanically stronger presspahn.

With smooth armatures driving horns must be provided on the periphery; these driving horns consist generally of metal strips, which are wrapped in presspahn, leatheroid, or the like, and driven into the milled slots (see Fig. 69). The driving horns should be placed in distances of about 6 to 10 cms.

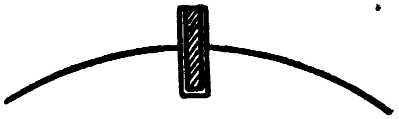


Fig. 69.—Driving Horn on Smooth Armature.

Both in smooth armatures and in armatures with open slots the windings must be kept down by means of bands of binding wires. Small armatures having partly closed slots do not require any binding wires, while these are nearly always provided with large armatures and partly closed slots.

In the case of slotted armatures the core is sometimes constructed with shallow channels around the periphery to receive the binding wires (see Fig. 70). For this purpose some of the core discs will be stamped with a slightly smaller external diameter, the reduction in the diameter being as a rule not more than about 2·5 mm.

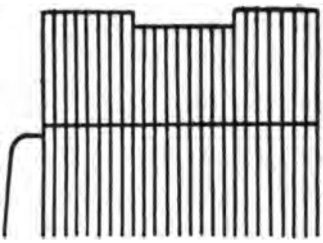


FIG. 70.—Channel for Binding Wires.

The binding wires must be very strong, as they have to resist the centrifugal forces of the conductors, which, especially with machines for higher speeds, may be very considerable. The materials commonly used for binding wires are steel, bronze, and phosphor bronze, and occasionally brass.

For large machines it is absolutely necessary that the area of the binding wires should be calculated. For this calculation the following formula may be used:—

$$A_w = \frac{Z a l v^2}{3400 D C} \quad . \quad . \quad . \quad . \quad (14.)$$

where

A_w = total cross-sectional area of the binding wires in sq. mm.

Z = total number of conductors on the circumference of the armature.

a = cross-sectional area of each conductor in sq. mm.

l = length of conductors in cm.

v = peripheral speed of armature in cm.

D = overall diameter of armature in cms.

C = tensile strength of the binding wire used in kg. per sq. cm.

The tensile strength for the different materials used is as follows :—

Brass wire	: 5000
Bronze wire	: 4600–7000
Phosphor-bronze wire	: 7000–8000
Steel wire	: 6500

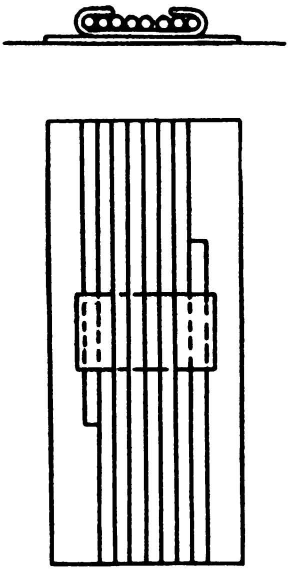


FIG. 71.—Band of Binding Wires.

Under each belt of binding wires a band of insulation must be laid, which should consist of one layer of very thin presspahn and another layer of mica. Under each belt of binding wires a thin strip of brass is also laid; and after the wire has been wound on the armature, the ends of these strips are turned over and soldered down to secure the two ends of the binding wire (see Fig. 71).

(b) MECHANICAL CONSTRUCTION OF ARMATURES

For holding together the core discs and keying them either directly or indirectly to the shaft, various methods are employed.

The simplest method is shown in Fig. 72. The shaft has a shoulder on one side, against which the brass or iron plate is resting. A central hole is pinched in the discs, the diameter of which is equal to that of the shaft. After the discs are pushed over the shaft, they are pressed together by another plate, which is kept in its position either by a hot ring, or, as in the case of

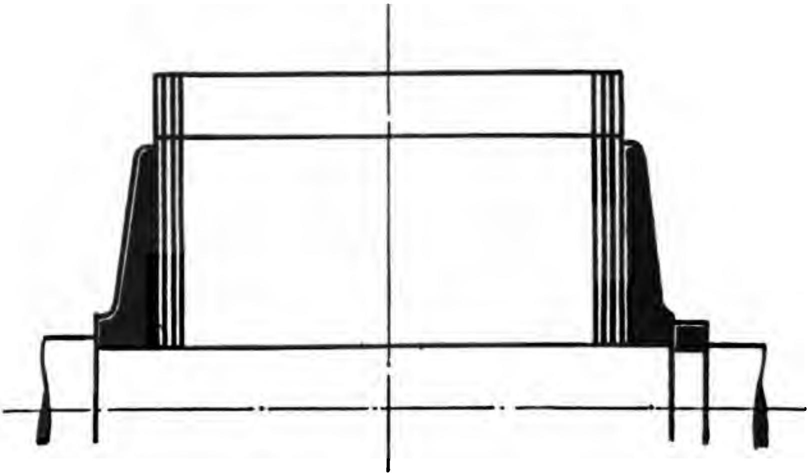


FIG. 72.—Armature Construction.

Fig. 73, by a nut. In the construction shown in Fig. 74 the end plates are omitted, and the discs are secured in

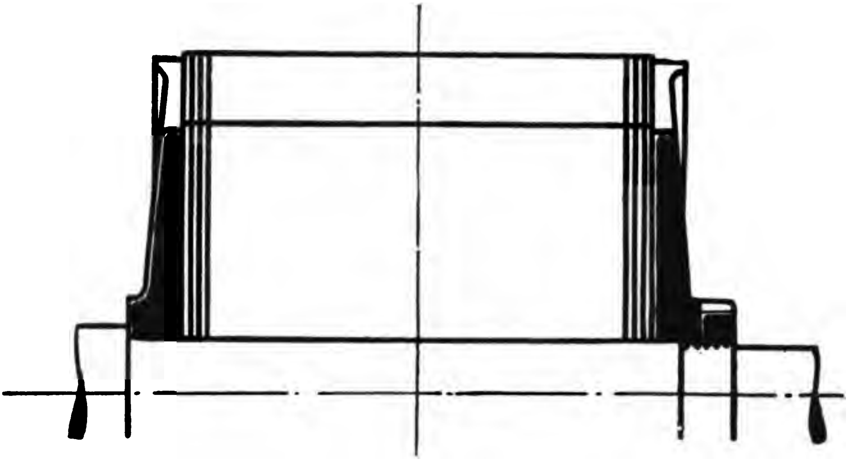


FIG. 73.—Armature Construction.

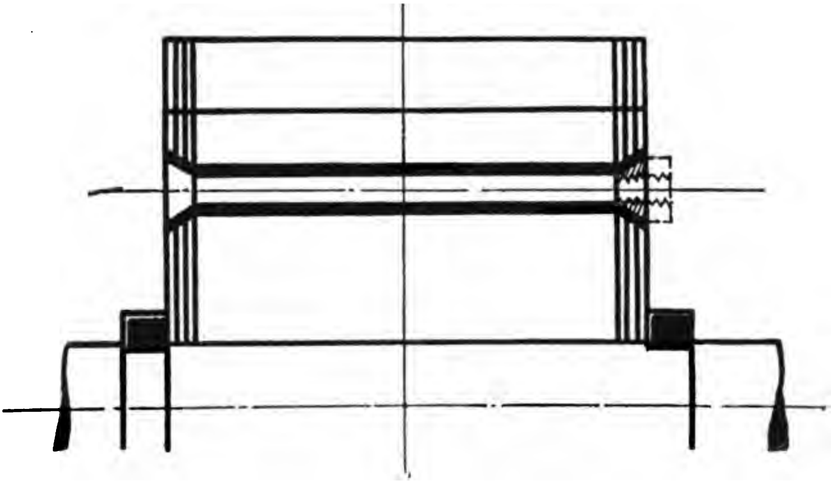


FIG. 74.—Armature Construction.

their position by means of two shrunk rings, and are kept together by a number of bolts; the latter should be insulated from the core by means of fibre tubes. In all the constructions shown in Figs. 72–74 the core is secured against a peripheral motion on the shaft by means of a key.

The types shown hitherto are, of course, used for comparatively small machines only; with large armatures it would be wasteful to make the discs full, and besides, the ventilation of the armature would be poor. On the other hand, the great simplicity and cheapness of this construction speaks very well for its application to even medium-sized armatures.

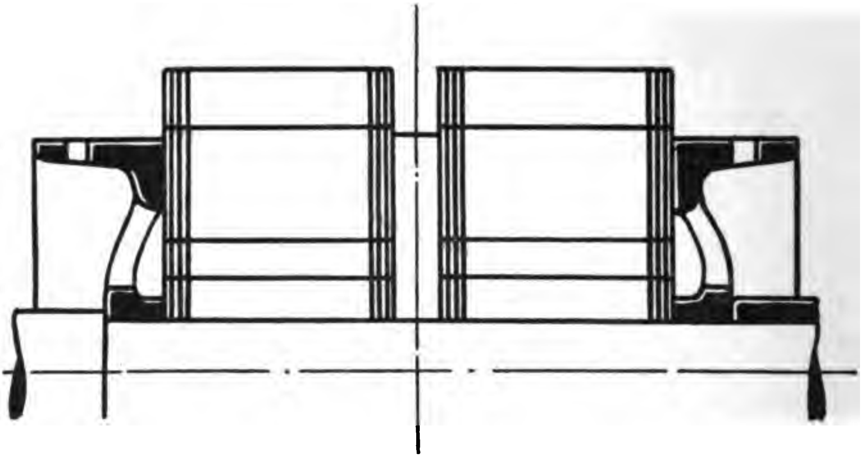


FIG. 75.—Armature Construction.

Fig. 75, for instance, shows the construction of an armature for a 10-KW. four-pole machine. The core discs are directly keyed on to the shaft, and are provided with holes for the ventilating ducts. Besides, the armature is divided into two parts by a central ventilating duct. The side rings or plates form at the same time brackets, on which the projecting winding is resting. The air-gap of this machine being very small, four binding wire channels are provided (not shown in the illustration).

As a rule the side plates do not cover the teeth, but terminate just below the bottom of the slots. In order to prevent a bending out of the teeth in the last few core discs, these are made somewhat thicker than the rest of the discs; the thickness of these last plates is generally about 1 mm.

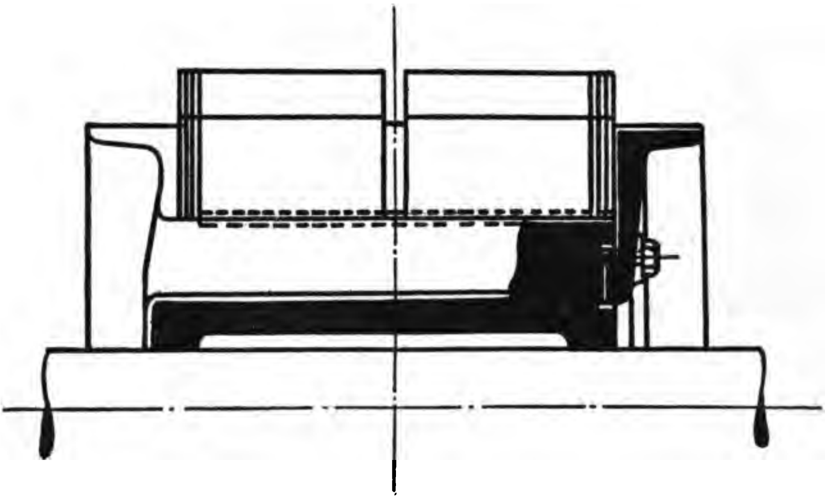


Fig. 76.—Armature Construction.

A similar construction to the last one, but suitable for larger armatures, is shown in Fig. 76. Instead of being keyed directly to the armature, the core discs are here keyed to a spider. One of the brackets and side plates is cast together with the spider, while the other bracket is fixed to the spider by means of screws.

A simple construction for a medium-size armature is shown in Fig. 77. This construction is suitable for evolute-wound armatures.

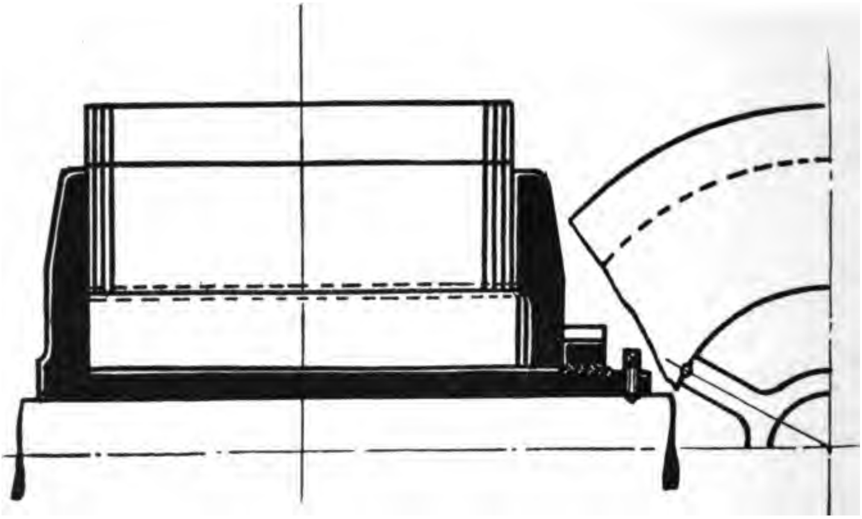


FIG. 77.—Armature Construction.

Another construction for a large evolute-wound armature is depicted in Fig. 78. The discs are kept in position by several keys; the end plates are kept together by means of screws, which do not pass through the discs, but just below them. An insulation of the bolt is therefore not necessary.

A somewhat similar construction for very large armatures (up to 2 to 3 m. diameter) for evolute windings is shown in Fig. 79. The stampings are kept in position by the wedge-shaped ends of the spider ribs.

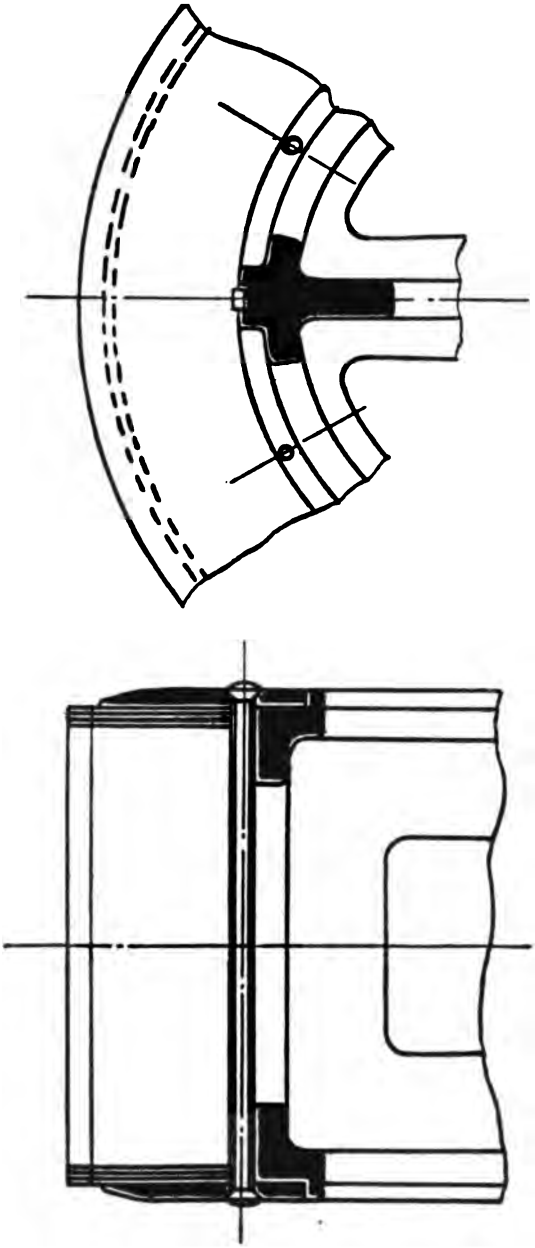


FIG. 78.—Armature Construction.

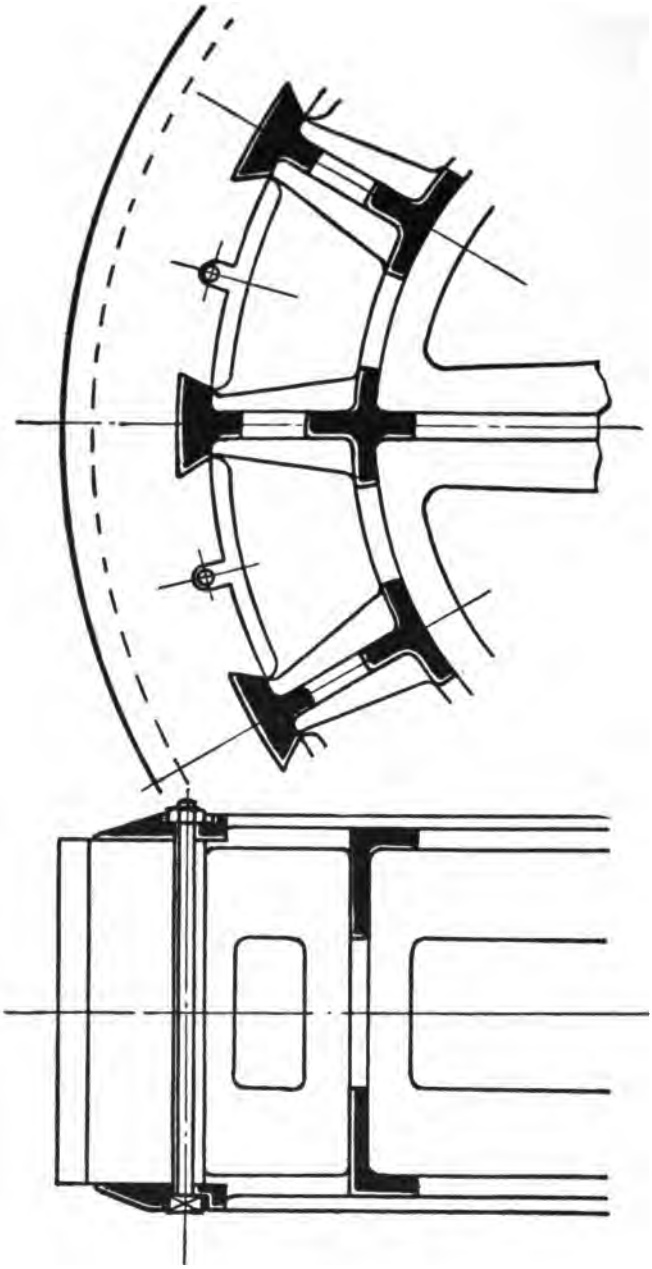


FIG. 79.—Armature Construction.

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